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SHOCK TUBE TESTS OF MUZZLE BLAST TRANSDUCERS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (ner)

A fairly extensive comparison testing of blast transducers is presented. A number of blast transducers were exposed to a series of shock waves from the BRL 58 cm shock tube. Both the angle of shock incidence and the incident pressure levels were varied during the tests. The purpose of the study was to check the transducer's response and accuracy when misaligned to the flow direction. The complete sets of pressure-time records for representative transducer types are presented. (continued)

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20. ABSTRACT (continued):

The results show that, in general, none of the tested blast transducers measures the static or side-on pressures accurately independent of orientation. As a consequence, continual attention must be given to optimal transducer orientation and other considerations relevant to the blast transducer used.

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I. INTRODUCTION

At a particular location behind a gun muzzle, a pressure transducer may record signals which arrive at transducer location only after diverse and varied interactions--with ground plane, with trails, with other blast waves, or with shields or obstructions from its own or from neighboring weapons. This means that a measurement of the "static" or "side-on" pressure whereby the measuring gage is aligned to the flow direction is practically an impossible feat over the duration of significant overpressure levels from the blast, since flow direction is changing in a manner depending on the various disturbances to the primary flow. Nevertheless, various people must have accurate information on these overpressures, particularly HEL and the Surgeon General's personnel who must look out for protection of gun crews, and weapon designers who must attempt predictions and assess the effects of weapons with and without various muzzle devices.

The present series of tests had the purpose to determine the effect of imperfect alignment of the measuring transducer to the blast wave direction. Thus, there might exist an optimum blast gage to measure these levels of overpressure which would read, even at some misalignment, close to the true side-on overpressure. It is of value to find or describe such a gage, if it exists. The confidence level would be enhanced in measurement over extended duration, as is often required. To approximate the blast loadings simply and predictably, gages were exposed to the quasi-steady pressures behind a shock in the BRL shock tube. A number of currently used blast gages and gages mounted in typical housing shapes were exposed to the shocked flow. A brief description of the shock tube and supporting recording apparatus follows, as well as some features of the various blast gages and housings used.

II. INSTRUMENTATION AND EXPERIMENT

A. Shock Tube

The BRL shock tube is a 57.5 cm (22.5 in) diameter tube going via an area-preserving transition section to a 51 cm (20 in) square cross sectional area test section.[1] The shock tube has velocity monitoring gages in its walls, the signals from which are entered into an on-line system to compute the overpressures behind the shock. Experience has shown velocities measured are within 1% of predicted values.

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1. *G. A. Coulter and B. Bertrand, "BRL Shock Tube Facility for the Simulation of Air Blast Effects," Ballistic Research Laboratory Memorandum Report 1685, August 1965. AD 475669.*

A transducer under test was hooked up to standard signal conditioning equipment. The signal then is fed into the basic signal acquisition equipment--a Honeywell 7600 Analog Tape Recorder with a Visicorder Strip Recorder to monitor and "quick-look." Several Nicolet digital oscilloscopes also monitored and "quick-looked" at each test run. The analog tapes are digitized off-line and processed to give pressure-time traces. Recording and processing are in accordance with standards set in Reference 2. The resulting data are presented in the next sections, grouped according to gage type or housing. First, however, we describe the mounting and positioning of gages in the test section.

B. Transducer Mounting

The gage mount is a metal arm or strut which hangs down from a circular close-off plate in the top wall of the test section, as sketched, Figure 1. The mounting holds the gage at tube centerline. The circular close-off plate is indexed to indicate angular settings with respect to tube axis. The gage orientation in degrees will be understood to be the angle between shock tube axis and (outward) normal to sensor/gage surface. Depicted, for example, is a gage in cylindrical holder at 0° angular setting, corresponding to "face-on" or normal incidence. A second example, following the prescribed nomenclature, depicts a pencil gage at 90° or "grazing" incidence.

In the shock tube wall at approximately the test station location is a fixed reference pressure gage, to give the true incident side-on pressure for every shot. Additionally, where test gage configuration permitted, the test gage was placed in the tube side-wall for certain of the shots to check response to true side-on pressure and to use as a normalizing value for the gage at other orientations.

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2. *G. A. Coulter et al, "Standardization of Muzzle Blast Overpressure Measurements," Ballistic Research Laboratory Special Publication ARBRL-SP-00014, April 1980.*

C. Transducers

The transducers available represented several different types of sensing element: quartz, ceramic, and semiconductor. Housing types were chosen to represent transducers 1) simply screwed into a holder, 2) baffled types such as discs or pancakes, and 3) pencil types. Figures 2-4 show the gage and housing types tested. All of the first group of Figure 2 were tested in the cylindrical holder shown, with a portion (about 0.5 cm) of the transducer case extending past the end of the holder. The Kistler transducer had a small taper from the cylindrical holder to the bare case. Figure 3 shows the disc baffle, into which transducers were directly mounted. The pancake type gage was one commercially available. Figure 4 shows the two pencil probe type transducers which could be directly mounted into the test mount. For reference, additional details of the transducers are given in the Table I.

D. Experiments

The experiments required exposing the gages to various pressure loadings, at fixed grazing orientation, as it would be in a field situation; then, exposure at a fixed loading as orientation of gage was changed.

The shock tube was operated as an air - air driven shock tube. The pressure range chosen was from 20.7 kPa to 103.4 kPa (3 psi to 15 psi) fixing at grazing incidence, while orientations ranged from 0° to 150° (as well as a few 180° shots), fixing at 34.5 kPa (5 psi) pressure. Note that in the context of hearing risk assessment the 5 psi level corresponds to about 185 db. This exceeds the "Z" curve of Mil. Std. 1474B (MI) for B-durations greater than about 5 ms. Thus, the gage is measuring over or near the upper allowed limits of most medium and large caliber weapons.

Table II gives the test matrix for the gages available. In the heart of the table are the identifying shot/run numbers mostly for BRL reference; they may not be consecutive because of other tests.

TABLE I. TRANSDUCER DETAILS

GAGE	SENSOR MAT'L	TYPE/ CONFIG	APPROX SIZE (cm)	APPROX RES FREQ-kHz	COMMENTS
Atlantic Res LC-33	Lead zirconate	Pencil	1.91 diam X 25.4	60	Sensing element is hollow cylinder polarized radially; shock mounted, has outer sheath for insulation and heat shielding.
Endevco 8510-15	Semiconductor	Miniature	0.38 diam X 1.6	100	Sensing element is active 4-arm piezoresistive bridge on silicon disc.
Kistler 201B5	Quartz	Miniature	0.56 diam X 3.6	250	Low impedance output.
PCB 113M28	Quartz	Miniature	0.56 diam X 3.1	500	
PCB	Quartz	Pancake	7.62 diam X 1.0	500	Sensing element is 0.56 cm diam.
Susquehanna Instr ST-2	Lead Zirconate	Bolt Stud	1.27 diam X 1.9	250	Sensing element is 0.32 cm diam.
ST-7	Lead Metaniobate	Pencil	2.22 diam X 35.6	250	Sensing element is 0.53 cm diam. flushed with flat surface milled the length of the pencil.

TABLE II. TEST MATRIX OF SHOTS

Type Transducer	Nominal Initial Overpressure, kPa: 34.5, α = 0°	40°	50°	75°	85°	90°	95°	150°	180°	Side on	20.7, 90°	48.3, 90°	68.9, 90°	103, 90°
PCB 113 M28	236	237	238	-	239 240	241	242	243	-	244 245	-	-	-	-
Susquehanna ST-2	246	247	-	-	248	249 255	250	251	-	258	252	253	254	256 257
Endevco 8510-15M 11A	70	71	-	-	72	73	74	75	-	81	76 77	78	79	80
Atlantic Res LC-33	87	86	-	-	84	82 83	85	88	-	-	89	90	91	92
Kistler 201B5 W/Disk	100	99	98	97	95	94	96	101	-	-	102	103	104	105
Kistler 201B5	108	109	-	-	110	113	111	112	-	107	114	115	116	117
PCB Pancake 113-A51	123	124	125	-	120	119	121	122	-	-	127	128	129	126
	90/90	90/40				90/0	90/5	90/150	90/180					
Susquehanna ST-7	137	133	-	-	-	130	132	135	150	-	-	-	-	-
	142	138	143	-	137 141	131	136	139 140	149	-	145	146 147	148	144
ST-2 W/Disk	-	-	-	-	152	151	153	-	154	-	-	-	-	-

Shot 238 was at shock incidence, α, of 52.5°.

Notation "90/40" for the ST-7 means grazing incidence (90°) and 40° yaw angle.

III. RESULTS

As mentioned, results for the gages are grouped according to type of sensor or housing -- i.e., cylindrical, disc or "pancake," or pencil. Comparison records for different gages within the types are shown. Additionally, the complete shot series for a representative sensor of a group are shown.

A. Cylindrical Type

In Figure 5 are shown typical pressure-time records for gages in cylindrical holders at or near grazing incidence to the flow, as might be attempted in a field measurement. The reference pressure is 34.5 kPa (5 psi)*. A characteristic to be noted in the traces is the lower value of pressure compared to the reference pressure, after some initial peaks. At increasing incident pressure levels, the pressures recorded become even lower, as exemplified in Figure 6, middle trace.

The gages here are apparently recording some effects of the cylinder's disturbance to the oncoming flow. Over the cylindrical surface the (steady, subsonic, isentropic) flow slows at the cylinder nose, then speeds up over the cylinder surface. Meanwhile, the pressure increases at the nose, then decreases as the flow expands around the cylinder, in accordance with the Bernoulli relation. The decrease in pressure over the cylindrical surface, together with possibly other effects, such as boundary layer transition and shifting of separation points, also tending to lower the pressure, must be convected over the end sensor surface to yield the lowered pressures as measured. At increased incident pressures one expects faster flows, yet greater expansions, and hence even lower pressures to be recorded compared to the reference. We note that an analytic description of the end flow over a cylinder is not available.

Additionally, one should remark on the poorer (lower) response of the Kistler gage--a 6mm (1/4 in) diameter cylinder--relative to the ST-2 gage--a 12.5mm (1/2 in) diameter cylinder. The Kistler gage presents less obstruction to the flow but apparently gives the flow less "recovery time" from the expansion over the end surface edges.

Typical records are shown in Figure 6 for the transducer response at the extreme orientations and (over) pressure levels. At face-on or 0° flow incidence one sees the initial, transient shock reflected pulse, then the decay to the stagnation pressure. At this level the reflected pulse is about 2.3 times the incident or side-on pressure, whereas the stagnation pressure is only about 12% higher, as the graph of Figure 7 shows (based on ideal, isentropic flow). At increasing angles, going to grazing or 90° incidence, the reflected pulse will go through a

**The reference wall pressure trace is labeled "PCB" since it is read out by a PCB quartz gage.*

maximum near 55° flow incidence, indicating a change of shock structure to Mach stem or triple shock formation. Thereafter, the reflected levels drop monotonically to the side-on value at grazing incidence. These features for the very localized, two-dimensional sensor surface are well known for the planar reflections of shocks in air[3,4] and values for the reflected pressure ratio vs. incident pressure and angle are reproduced in Figure 8.[5]

At flow incidence angles beyond grazing, i.e., with the sensor facing more or less backwards to the flow, one might expect a base-flow type of measurement, for which, depending on the pressure level and gage geometry, expansions around to the base region could lead to pressures lower than true side-on. Such is seen in the bottom record of Figure 6. In Figure 9 is presented a complete shot series for the ST-2 gage tested of this group. Figure 9a compares the sidewall response of the gage with the reference PCB gage, also mounted in the sidewall. The following Figures 9b-g are a set using a fixed 34.5 kPa (5 psi) incident overpressure level and observing the response as the gage orientation is varied with respect to the direction of shock propagation. Figures 9h-l illustrate the response at a fixed side-on orientation as the incident pressure level is varied. The specific test conditions are given on the top of each trace.

B. Disc and Pancake Type

Results from the disc and pancake type transducer holders are shown in Figure 10 for near grazing incidence (85° - 95°). Both records from the disc holders follow the side-on reference record reasonably well, as does the pancake gage record at 95°. However, at 85° and 90° the pancake gage record developed peaks and valleys similar to those recorded with the cylindrical holder.

Figures 11 and 12 show the changes in pressure recording for the extremes of orientation and pressure tested. The disc holder of Figure 11 appears to work poorly at the extreme orientation as might be expected since the holder represents a large disturbance to the flow, but does work quite well at the highest pressure tested, at grazing incidence.

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3. *J. von Neumann, "Oblique Reflection of Shocks," Bureau of Ordnance Explosives Research Report 12, 1943.*

4. *H. Polachek and R. J. Seeger, "Regular Reflection of Shocks in Ideal Gases," Bureau of Ordnance Explosives Research Report 13, 1944.*

5. *S. Glasstone (Editor) The Effects of Nuclear Weapons, Dept. of Army Pamphlet 39-3, April 1962.*

The pancake transducer, Figure 12, performed poorly, also, at the extreme orientation. At grazing incidence a small initial peaking seemed no worse at the maximum pressure tested than at the minimum. Figure 13 exhibits the response of a PCB pancake-type gage for the complete shot series.

C. Pencil Type

Figure 14 shows records from the two types of pencil transducers tested, at near grazing incidence (85° - 95°). The pressure traces from the LC-33 follow the reference pressure traces quite well except for the slower rise time. The sensitive element of the transducer is large compared to the other transducers tested. Thus flow "crossing times" are longer, and a slower initial rise in pressure sensed is a result. It should be noted that the ceramic sensor element of the LC-33 is sensitive to ambient temperature and would require on-site calibration just prior to its use in any tests. At the least, a temperature correction would be needed. (The same comments apply to the ST-2 since it also has a ceramic element.)

The LC-33 was relatively insensitive to extreme angle variations as seen by Figure 15. It was most inaccurate at 0° and 150° flow incidence angles. At grazing incidence the extreme pressure levels were tracked very well, it is seen. The flat side of the ST-7 at 0° and 150° flow incidence responded much as did the disc holders, having an initial (but much narrower) peak at these angles; however, the ST-7 worked very well at near grazing angles.

Figure 16 shows results for the ST-7 with the flat held in "up" position--grazing to the flow--then yawed from the vertical plane (notation: 90°-(yaw angle)). The pressure level is 34.5 kPa. The ST-7 gave comparable results at the 5° yaw angle, as well as performed well at the highest test pressures. Figure 17 shows the response of an LC-33 pencil-type gage for a complete shot series.

IV. SUMMARY AND CONCLUSIONS

A fairly extensive comparison testing of blast transducers is presented. A number of transducers mounted in various housings or holders--cylinder, disc, pancake, and pencil--were exposed to a series of shock waves from the BRL 57.5 cm shock tube. Both the angle of shock incidence and the incident (over) pressure levels were varied during the tests.

Pressure-time records from each of the transducer configurations were compared for each shot to the output from a flush-mounted reference transducer in the shock tube wall.

The cylindrical holder caused a low pressure deviation, even at grazing incidence of flow, from the reference pressure after the initial shock front passage. The deviation became worse as the incident pressure was increased.

The disc holder gave almost no disturbance at grazing incidence of flow for the pressure levels used. However, the large reflecting surface at non-grazing angles caused quite large deviations from the true side-on pressure.

The pancake transducer of the tests did not perform quite as well as the disc at any of the test conditions. Overshoot peaks occurred at grazing incidence. This was probably caused by the long bevel leading to the sensor element side of this particular transducer.

Both the pencil transducers performed well at angles near grazing incidence. The LC-33 suffered from a slow rise time because of its relatively large sensing element. The ST-7 suffered from peaks and pressure dips at the extreme orientations.

In general, none of the transducer configurations tested had the ability to measure pressures accurately independent of orientation. None seemed to be clearly superior at the levels and orientations tested. A disc-type holder does offer the possibility of measuring side-on blast pressures accurately in a single plane--the plane of the disc. Any angular flow deviation out of the plane beyond ± 5° from grazing incidence will cause distortion of the true side-on pressure-time profile. For simplicity and convenience, either the pencil-type or cylindrical transducer may be adequate, with due regard given to risetime and low readings (and temperature corrections). (The LC-33 pencil gage has been ruled out according to the recommendations in Reference 2 due to element size and resonant frequency. Were a higher resonant frequency sensing element available, the recommendations in Reference 2 may be premature.) Development of an accurate, omnidirectional blast transducer seems yet in the future.

a.

b.

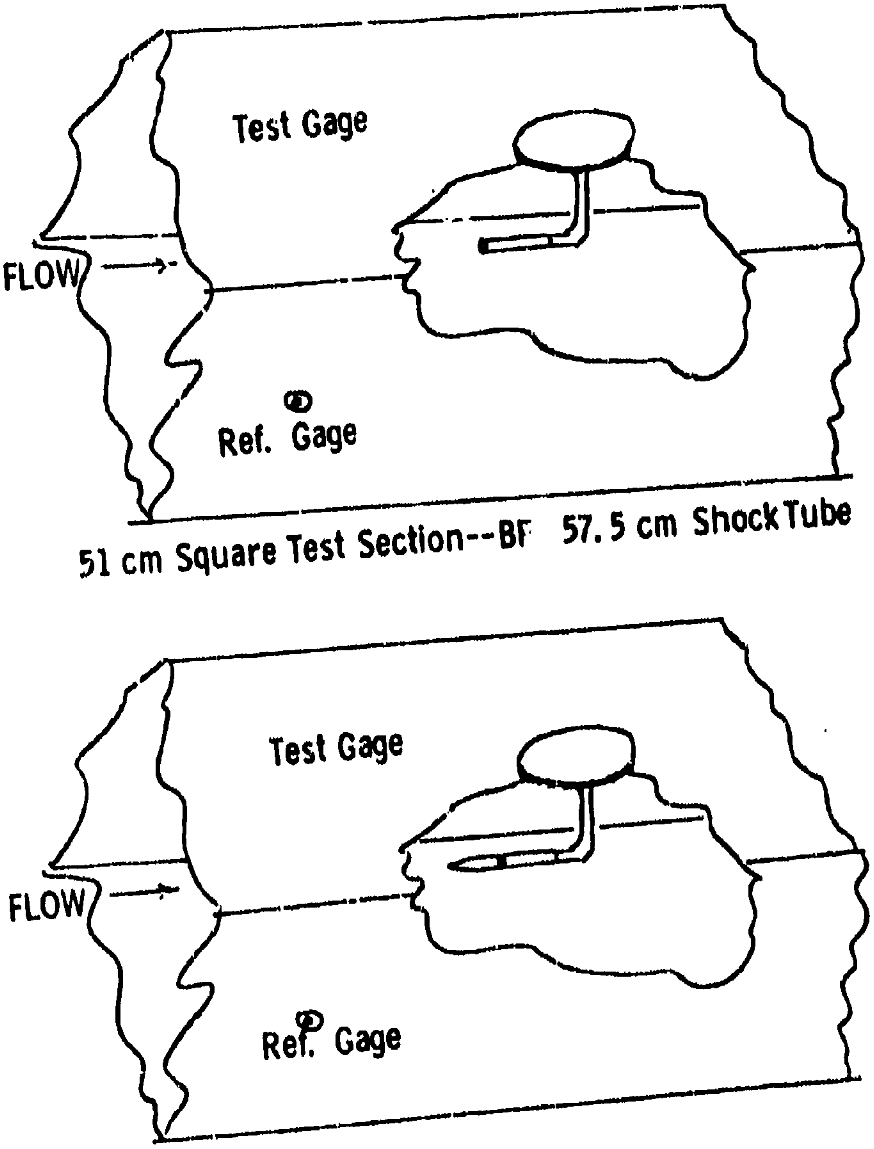


Figure 1. Transducer Mounting in Shock Tube

a. Cylindrical Probe at 0°

b. Pencil Probe at 90°

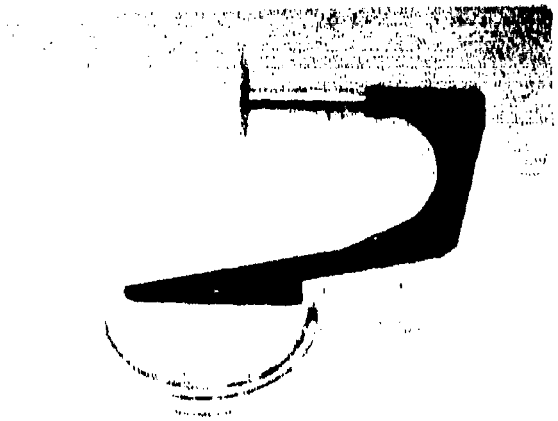
a.

b.

Figure 2. Miniature Transducers:

a. Front--Endevco; Middle--ST-2; Back--PCB

b. In Cylindrical Holder and 12.5mm Diameter Adaptor as Required a



b

Figure 3a. Transducer in Disc Mount

b. Pancake Type Transducer

Figure 4a. Pencil Gage, LC-33

b. Pencil Gage, ST-7

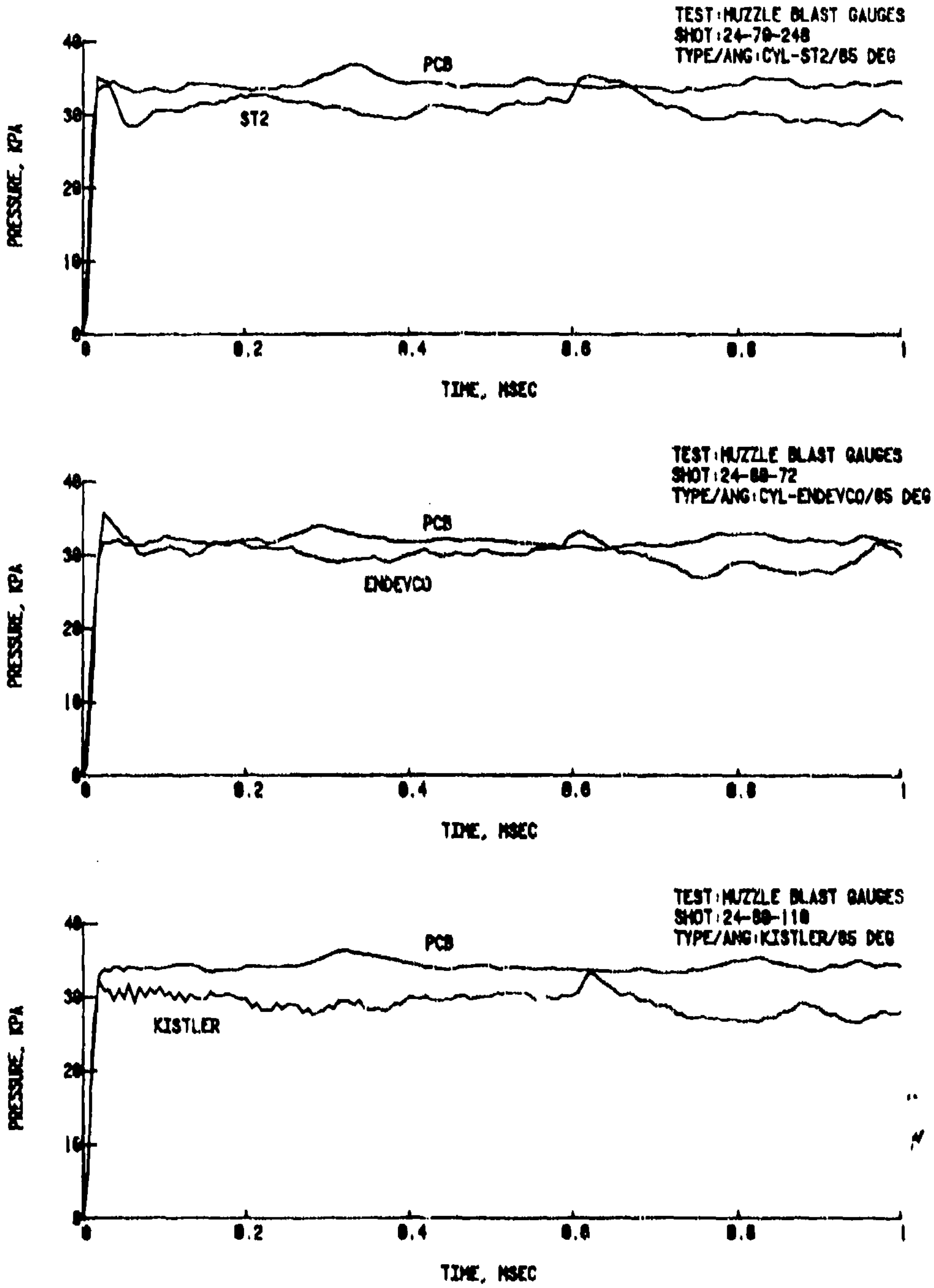
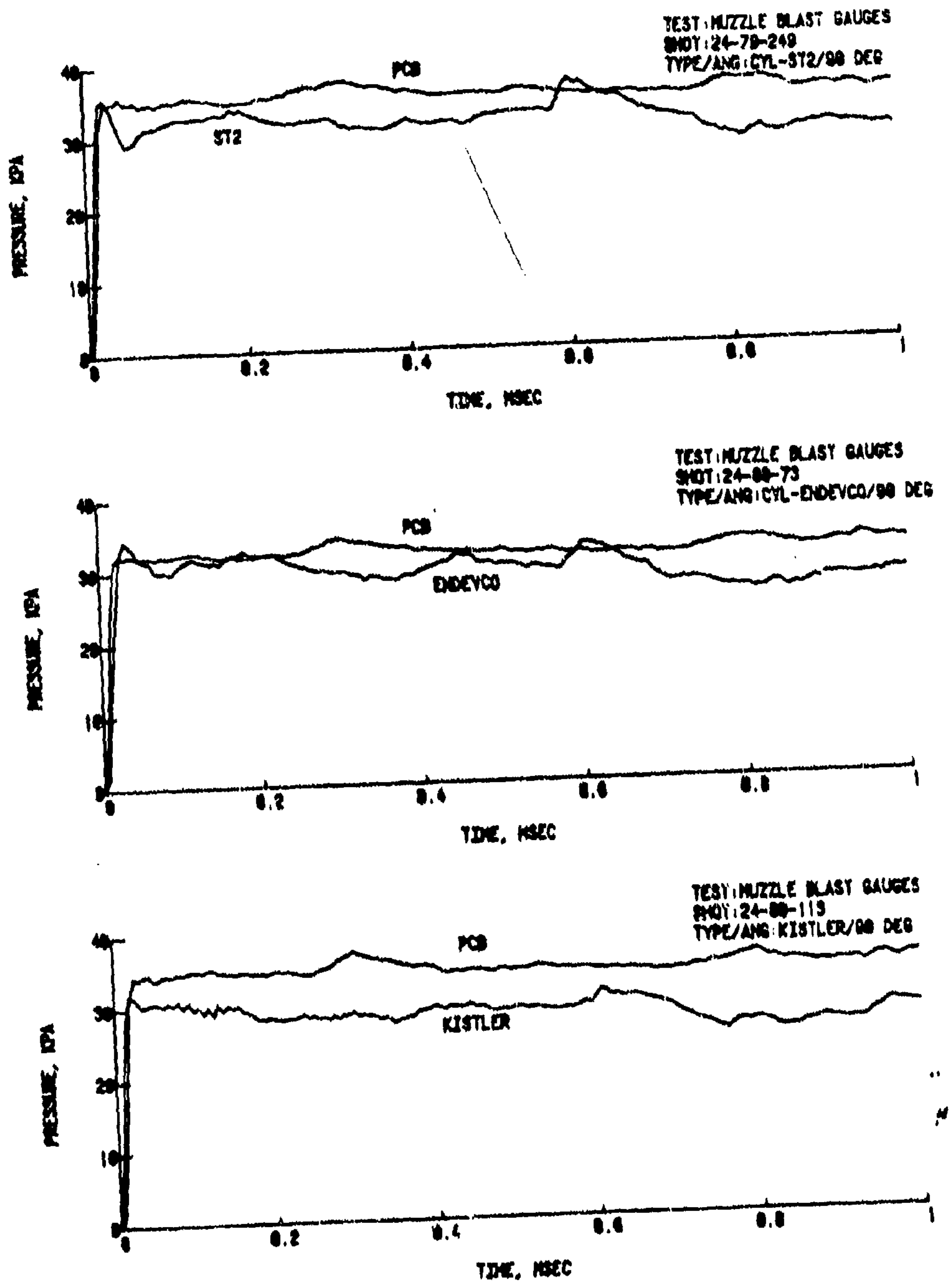
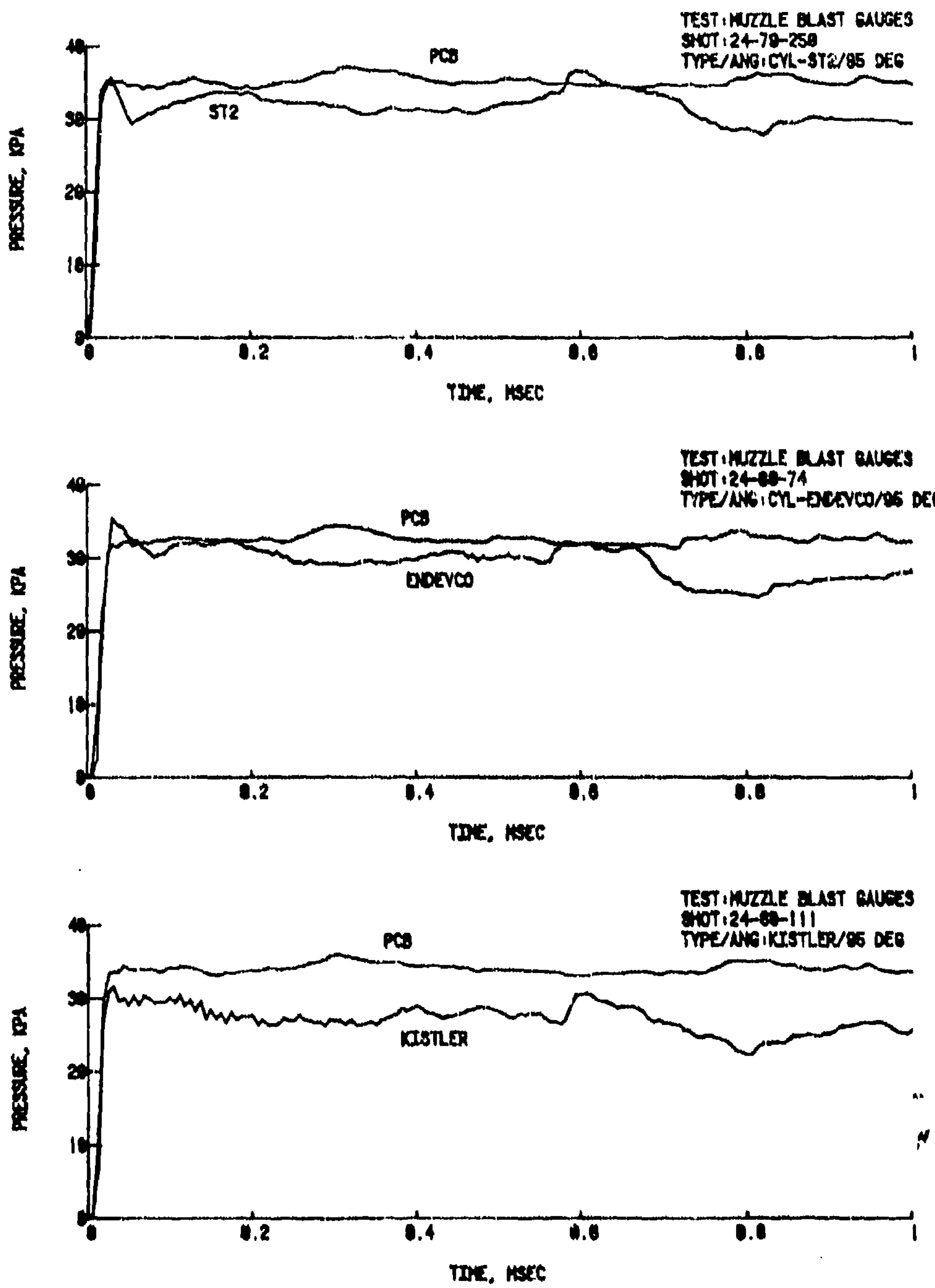


Figure 5. Comparisons for Transducers in Cylindrical Holder, for Flow Near Grazing Incidence

a. At 85°



b. At 90° or Grazing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PCB
ST2
PRESSURE, KPA
TIME, MSEC
TEST:MUZZLE BLAST GAUGES
SHOT:24-80-74
TYPE/ANG:CYL-ENDEVCO/95 DEG
PCB
ENDEVCO
PRESSURE, KPA
TIME, MSEC
TEST:MUZZLE BLAST GAUGES
SHOT:24-80-111
TYPE/ANG:KISTLER/95 DEG
PCB
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TIME, MSEC

c. At 95^{o}

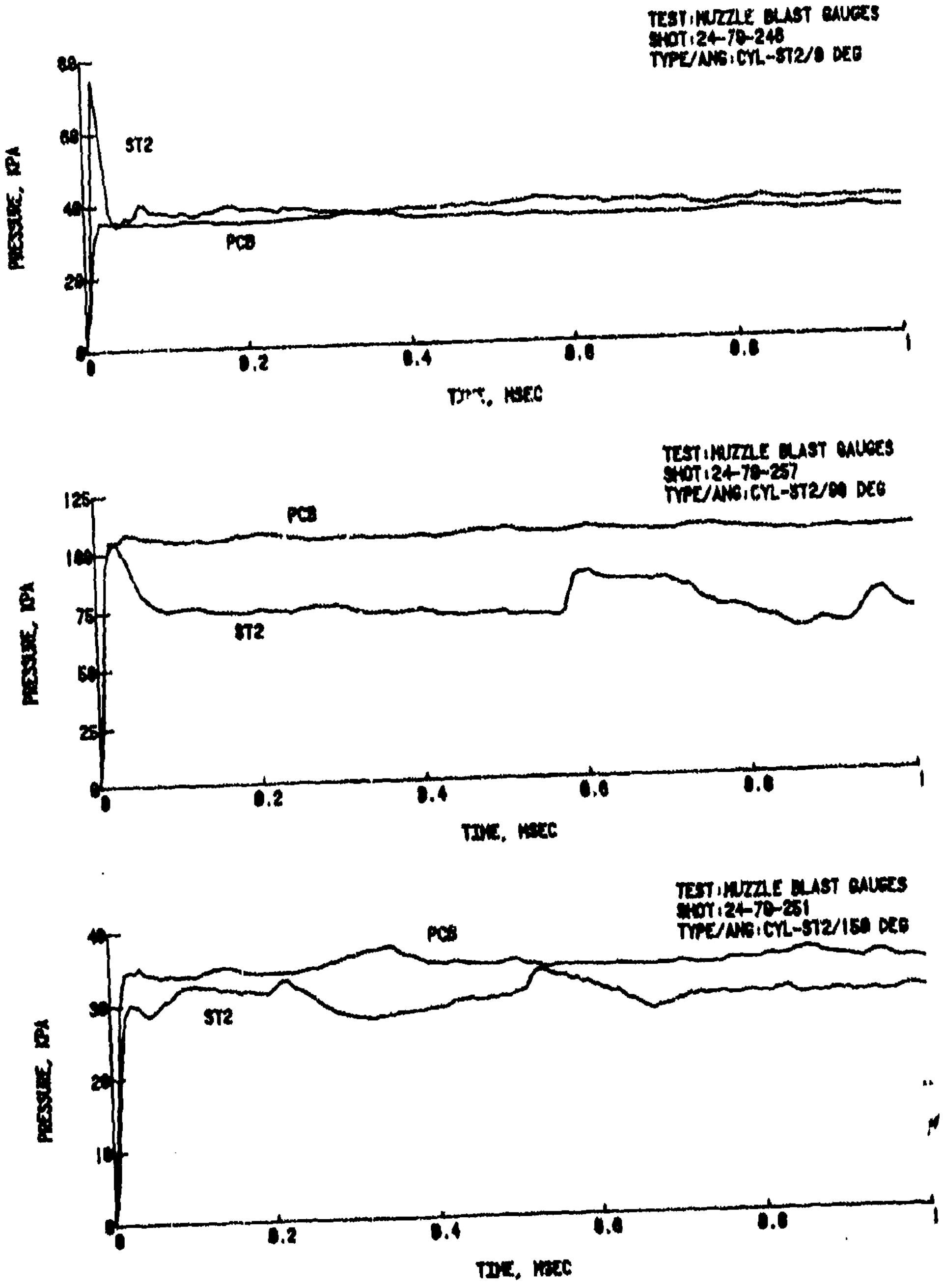


Figure 6. Deviations from True Side-on Pressure, Cylindrical Holder

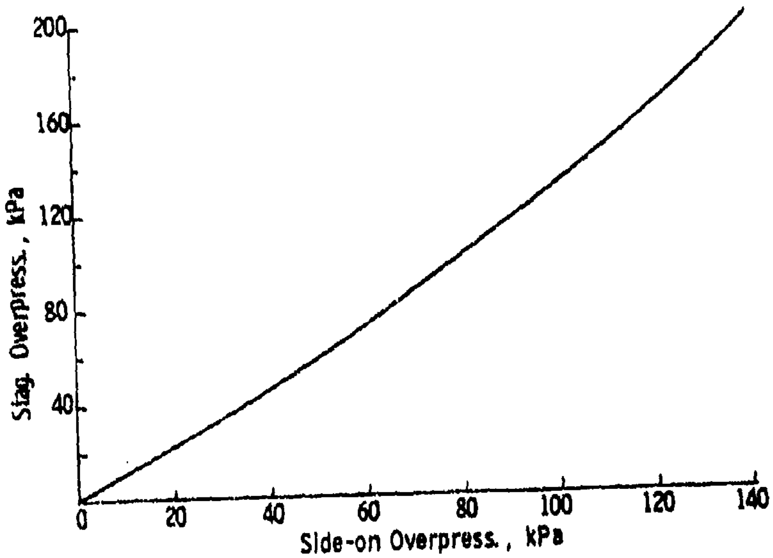


Figure 7. Dependence of Stagnation Overpressure on Incident Overpressure

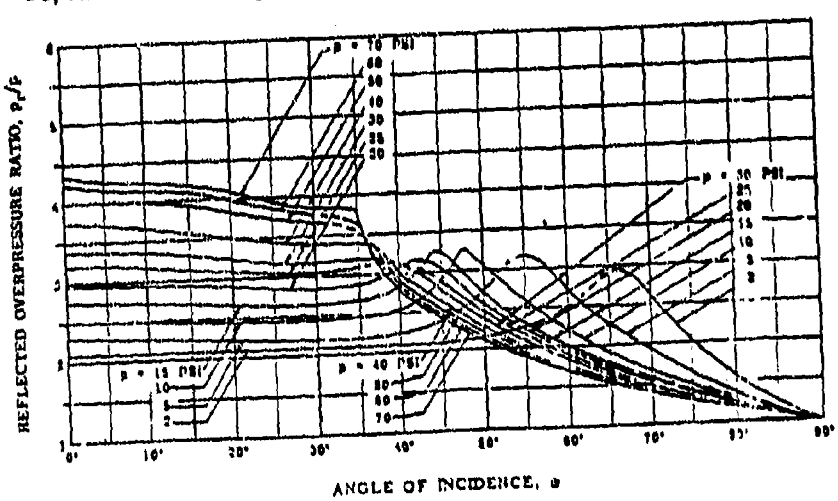
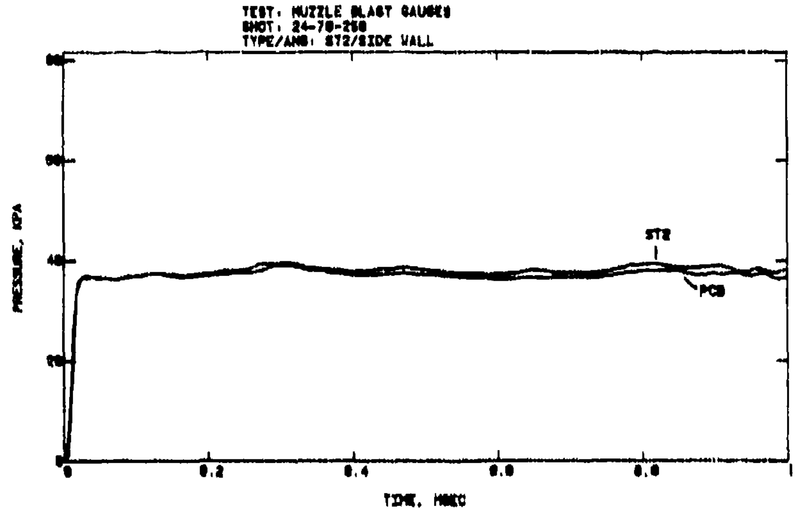


Figure 8. Dependence of Reflected Overpressure Ratio on Incident Overpressure and Flow Angle



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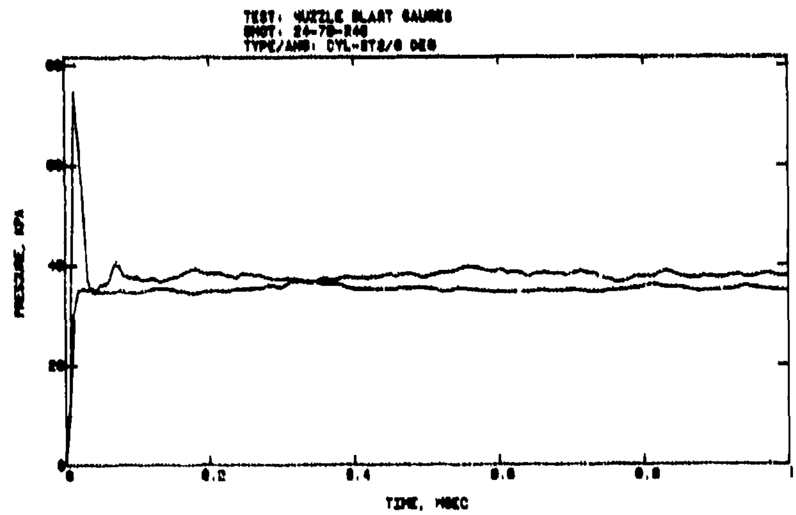
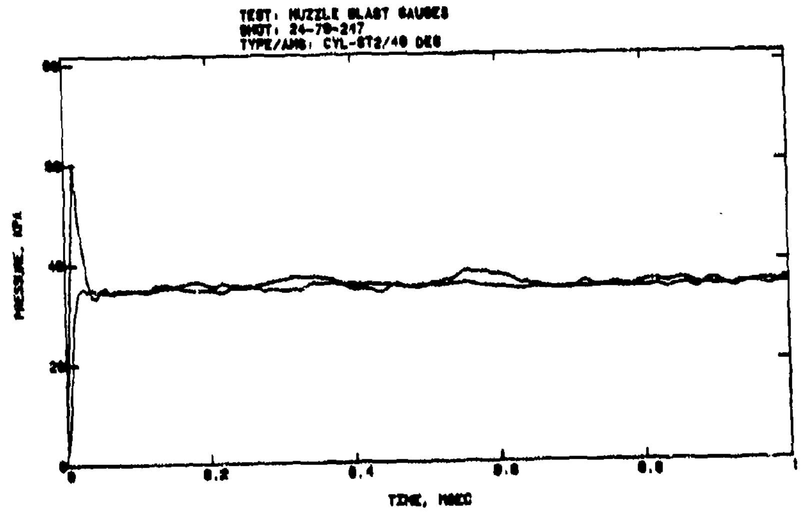


b.

Figure 9. Complete Shot Series for Cylinder-Type ST-2 Gage



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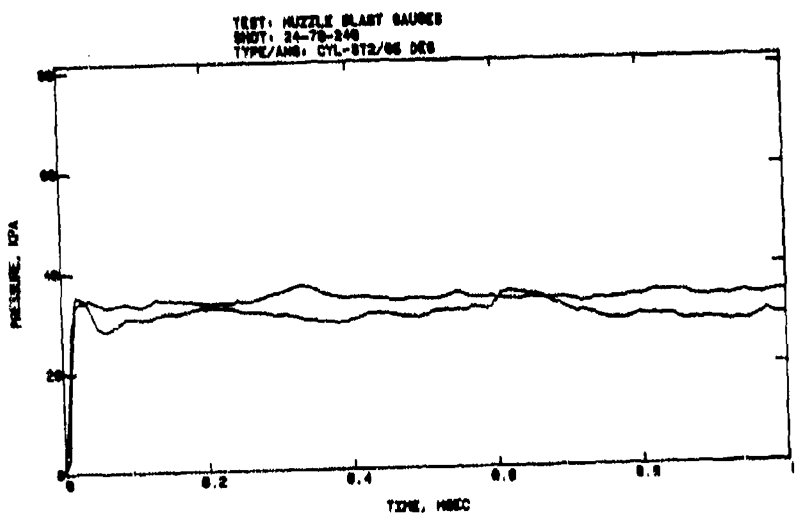
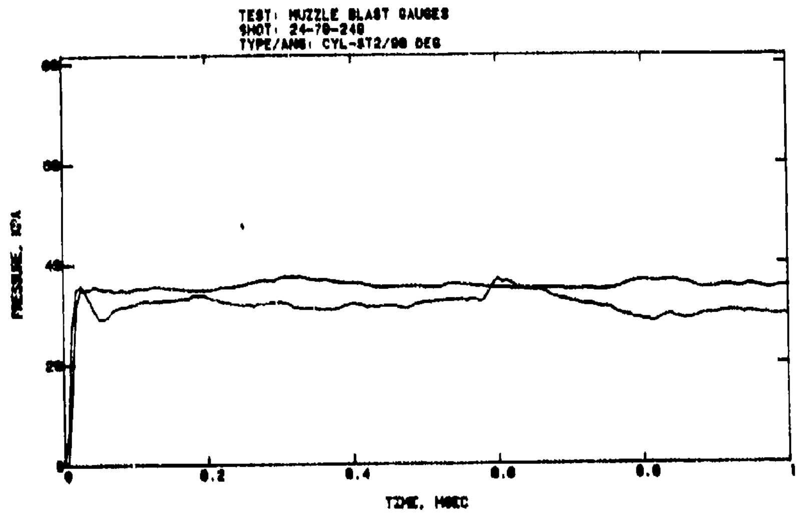


d.

Figure 9. Continued



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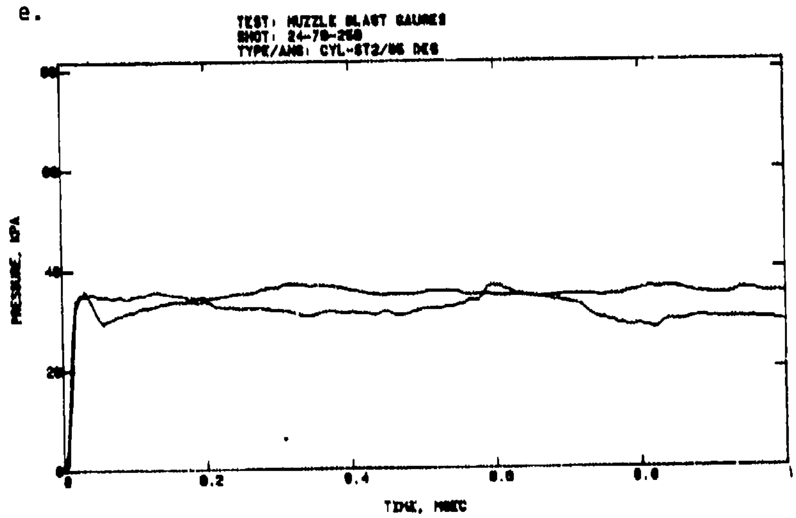

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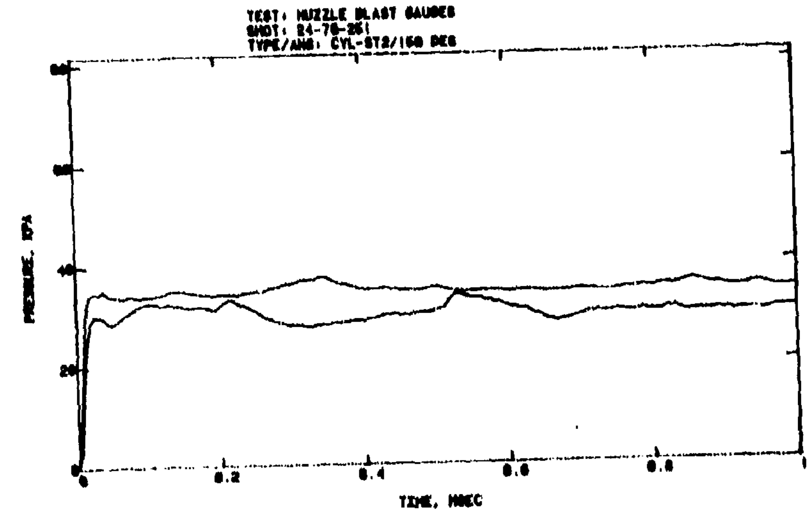

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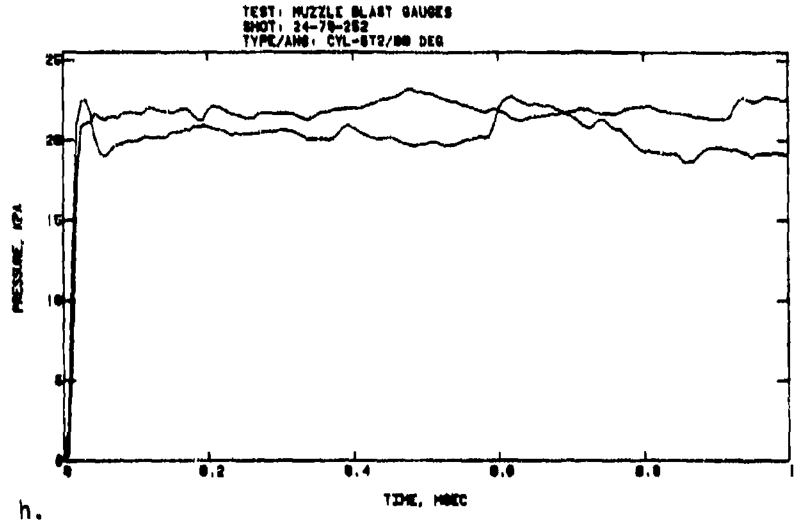

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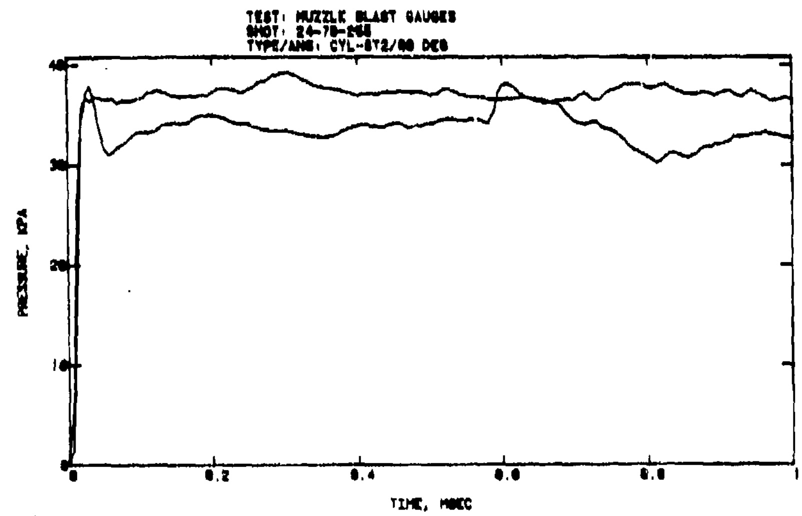

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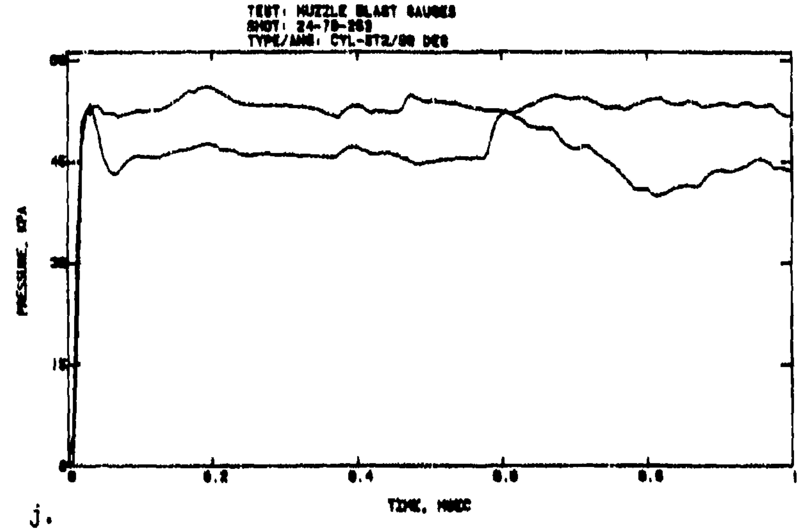

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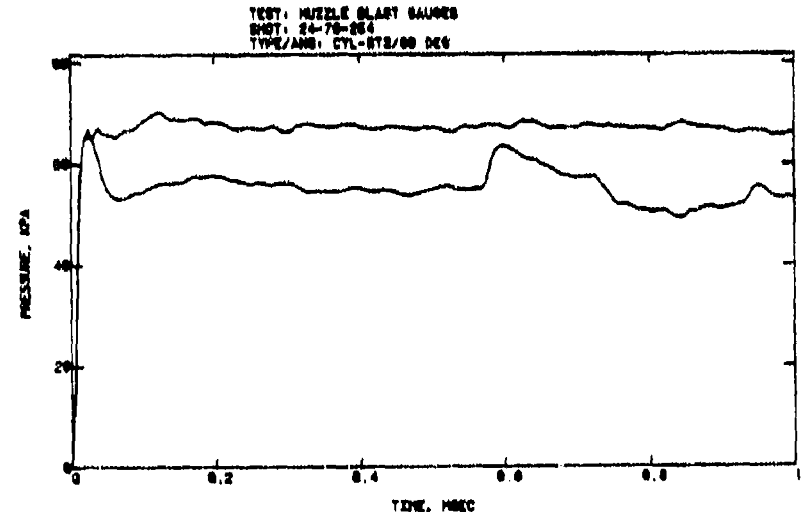

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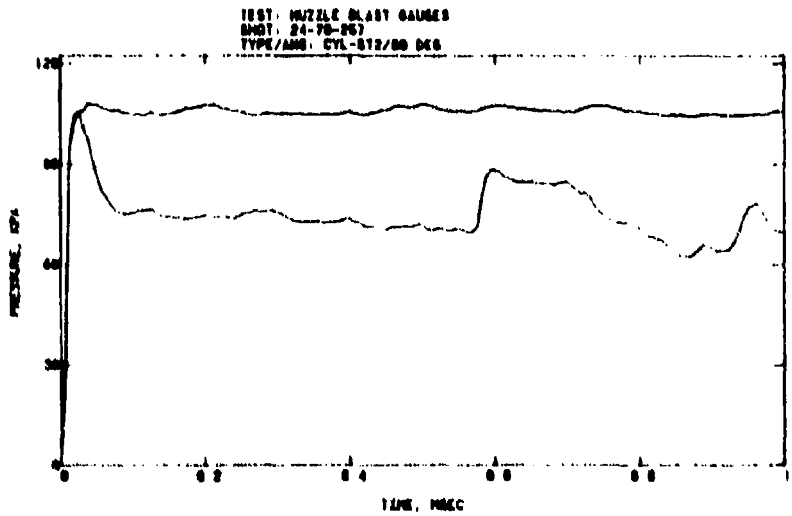

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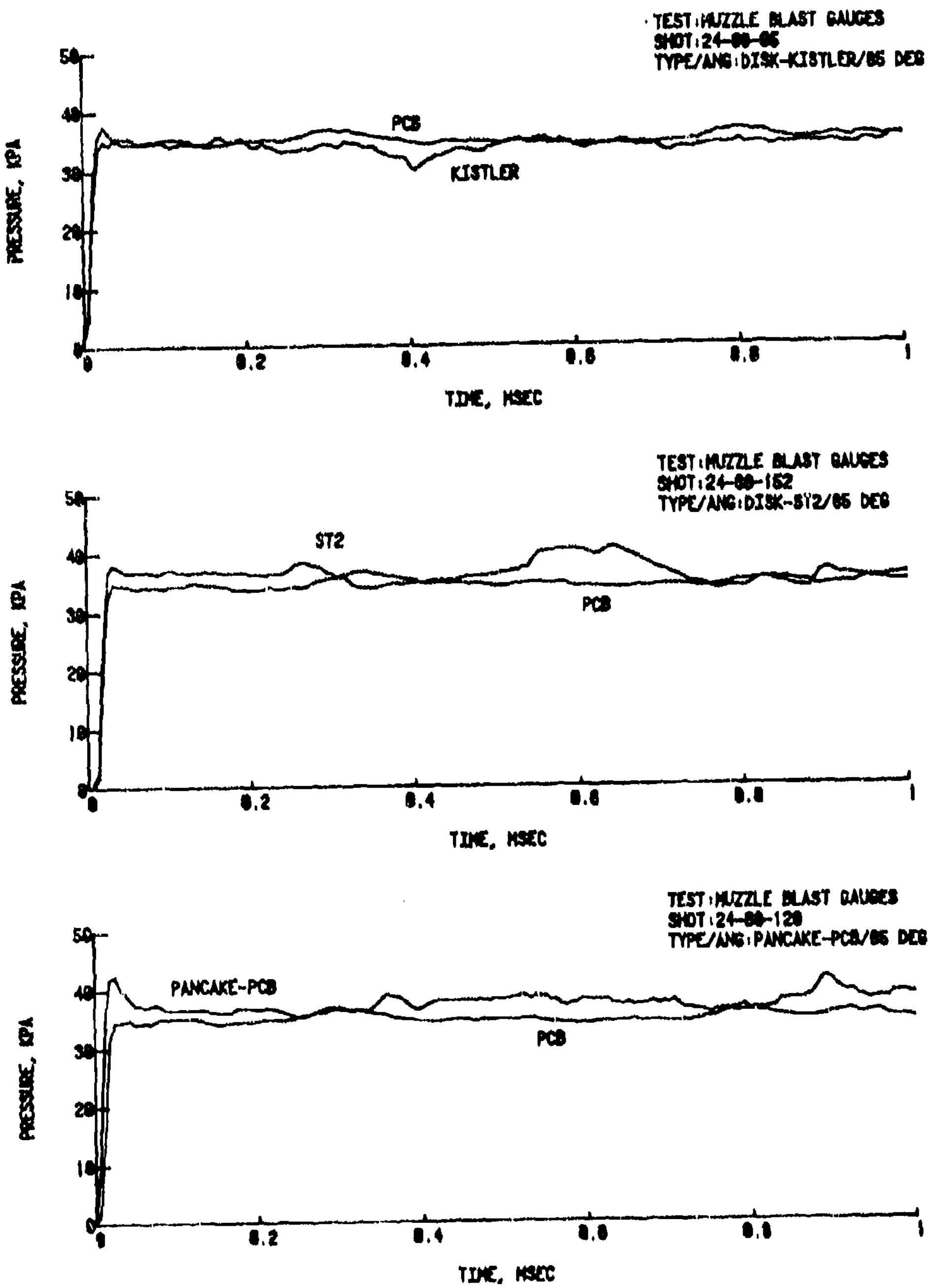
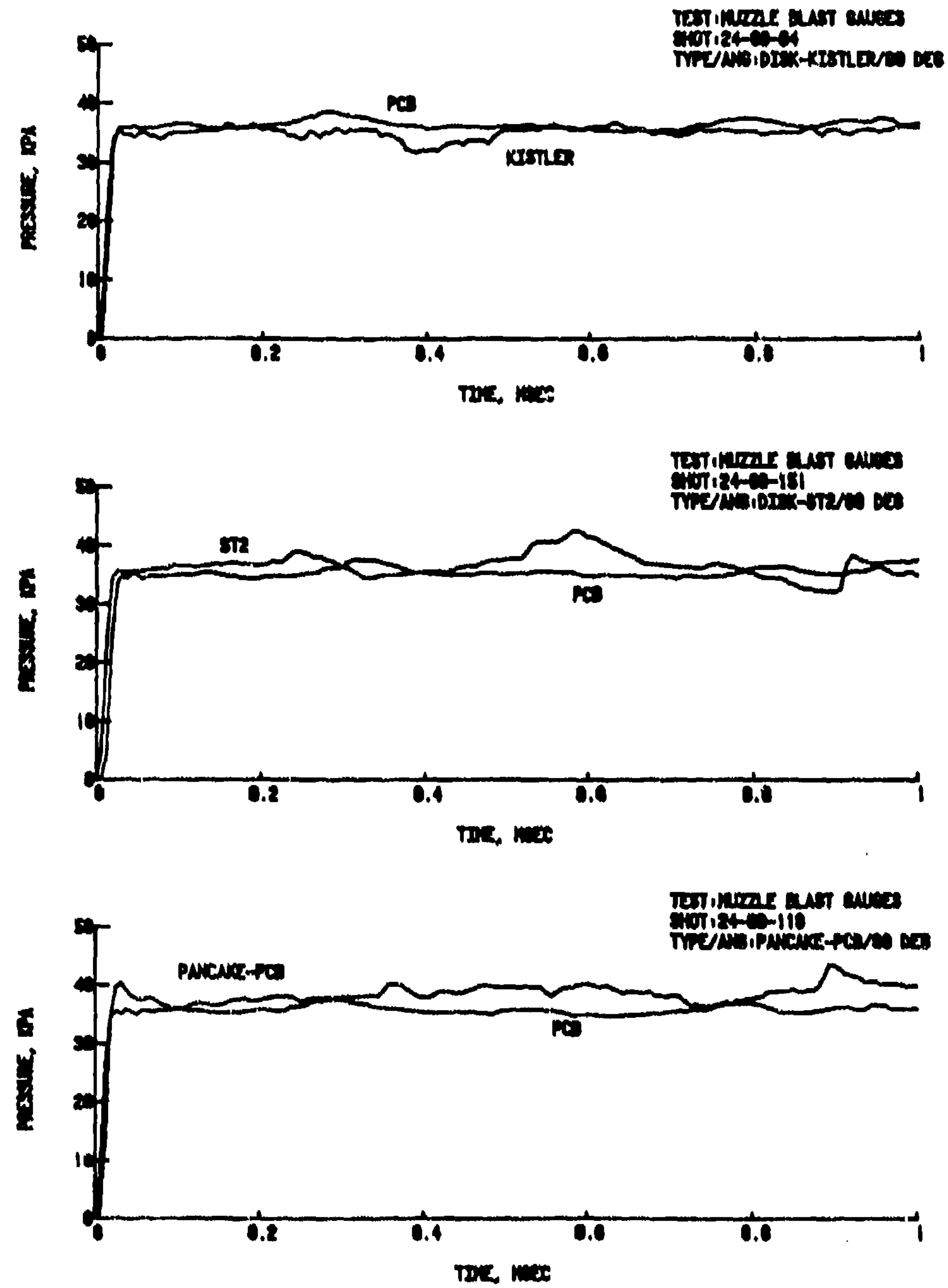
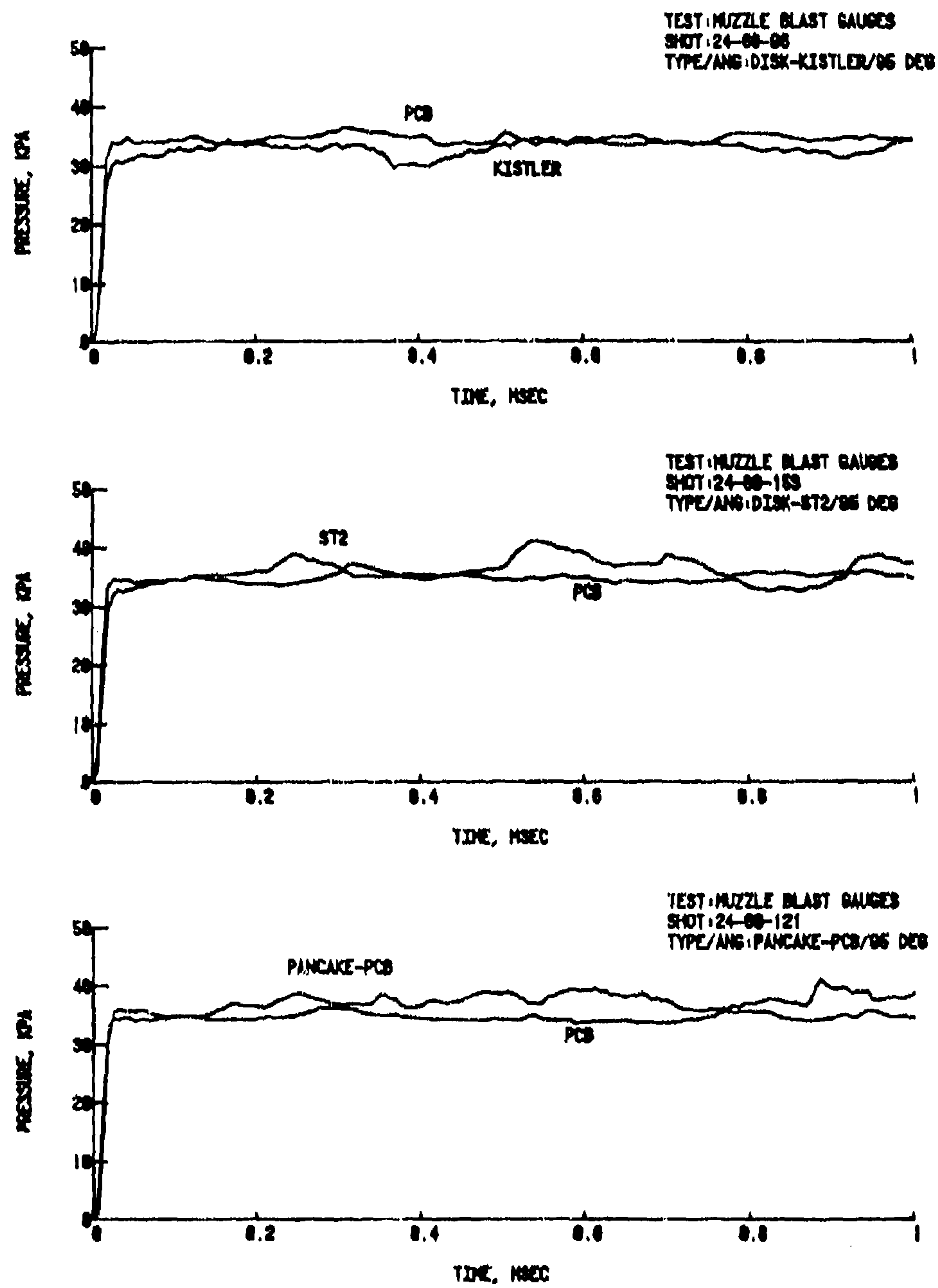


Figure 10. Comparisons for Transducers in Disc- or Pancake-Type Holders, for Flow Near Grazing Incidence

a. At 85°



b. At 90° or Grazing


TEST:MUZZLE BLAST GAUGES
SHOT:24-88-86
TYPE/ANG:DISK-KISTLER/95 DEG
PCB
KISTLER
PRESSURE, KPA
TIME, MSEC
TEST:MUZZLE BLAST GAUGES
SHOT:24-88-153
TYPE/ANG:DISK-ST2/95 DEG
ST2
PCB
PRESSURE, KPA
TIME, MSEC
TEST:MUZZLE BLAST GAUGES
SHOT:24-88-121
TYPE/ANG:PANCAKE-PCB/95 DEG
PANCAKE-PCB
PCB
PRESSURE, KPA
TIME, MSEC

c. At 95^{o}

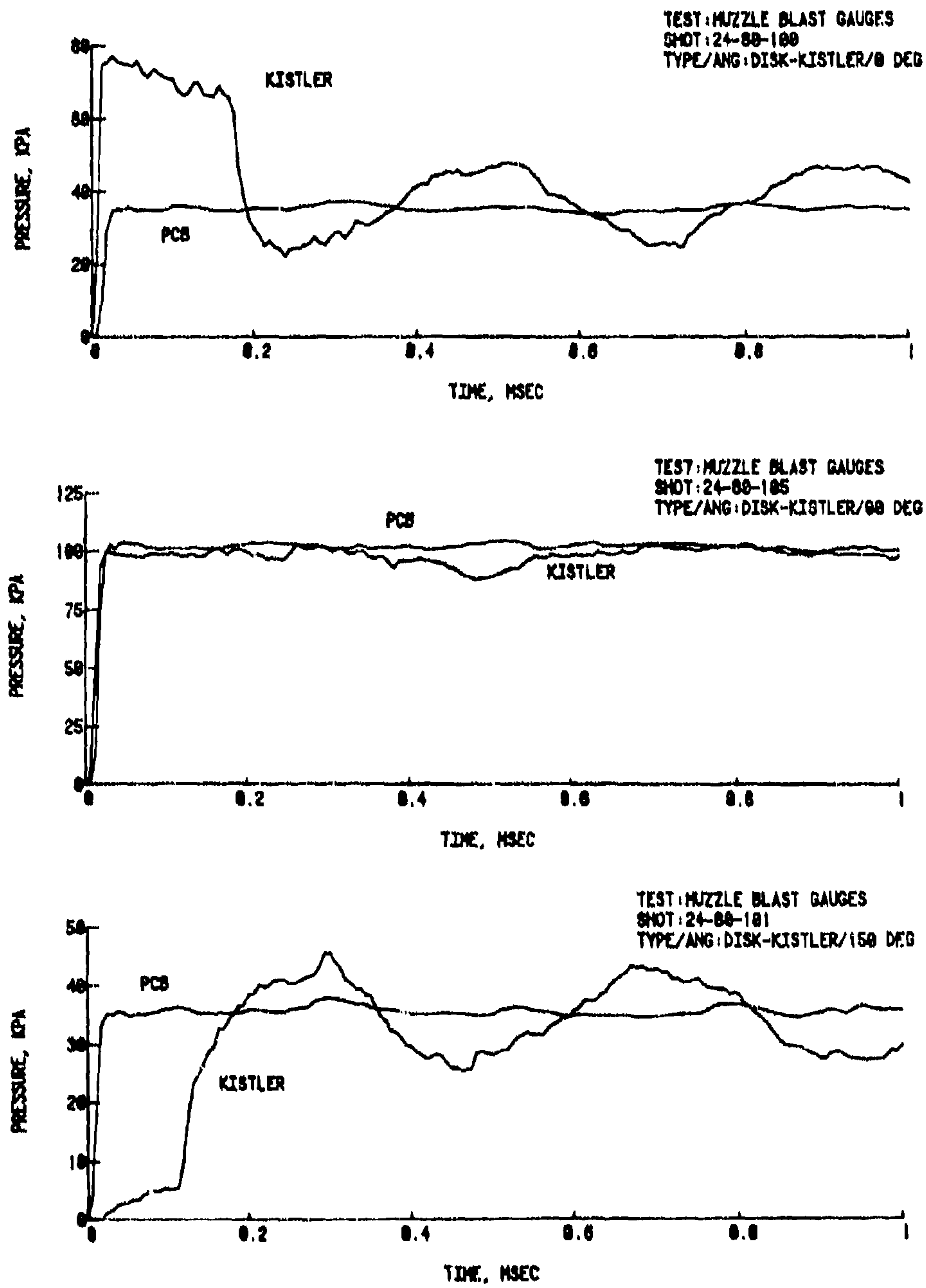


Figure 11. Deviation from True Side-on Pressure, Disc Holder

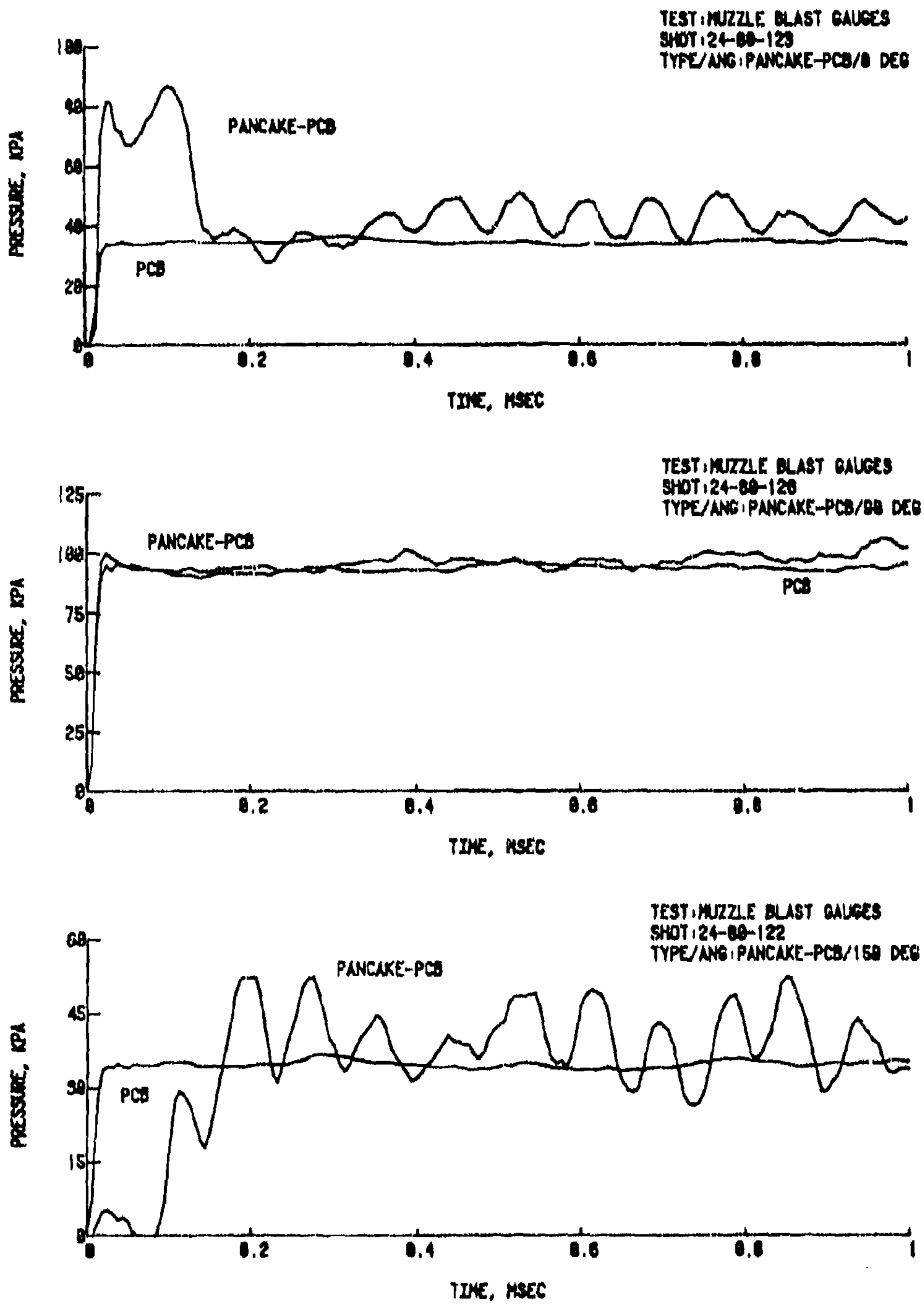
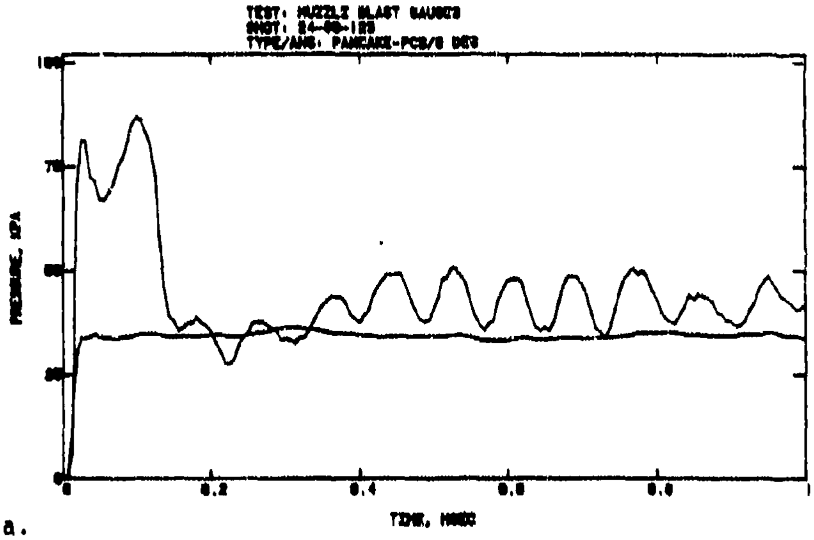
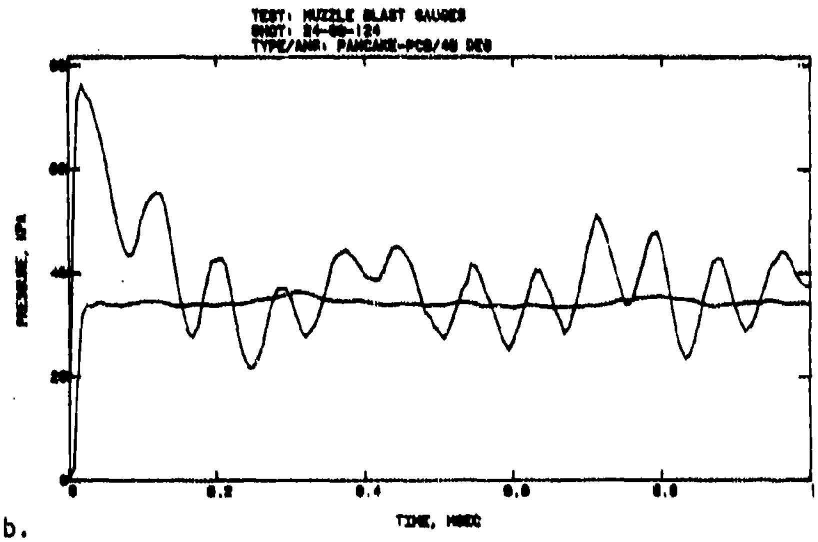


Figure 12. Deviation from True Side-on Pressure, Pancake Transducer

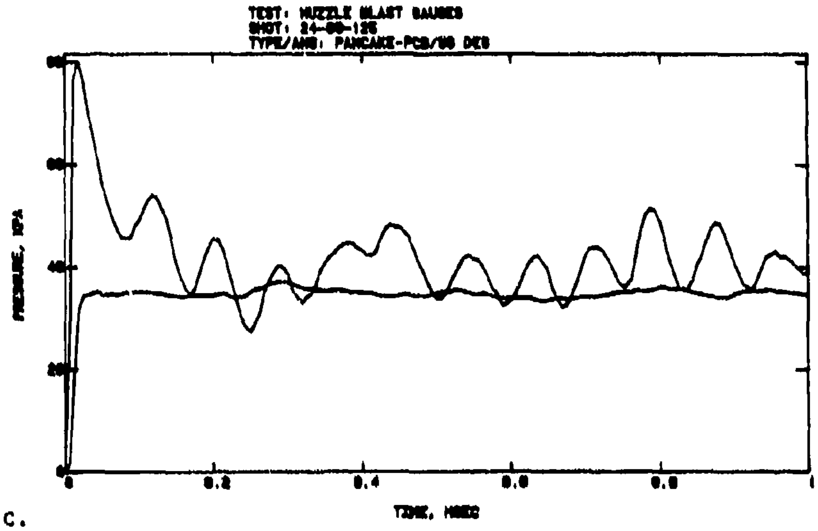


a.

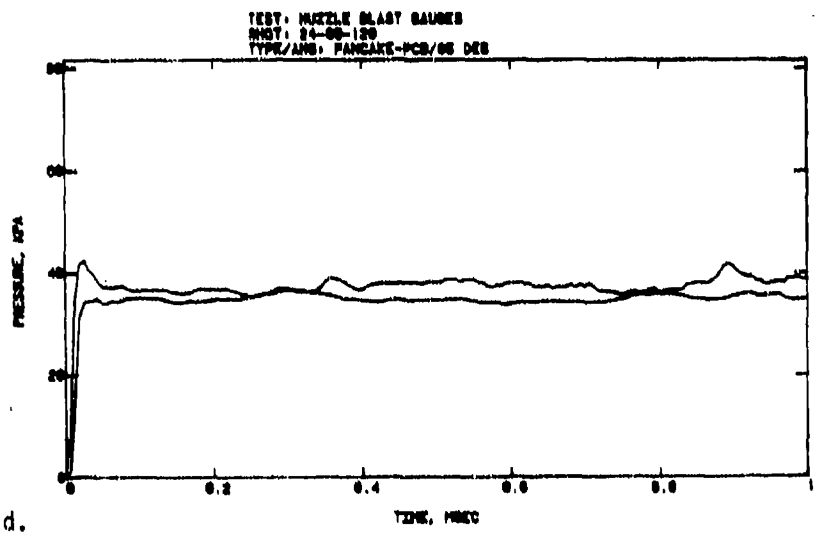


b.

Figure 13. Shot Series for PCB Pancake-Type Gage

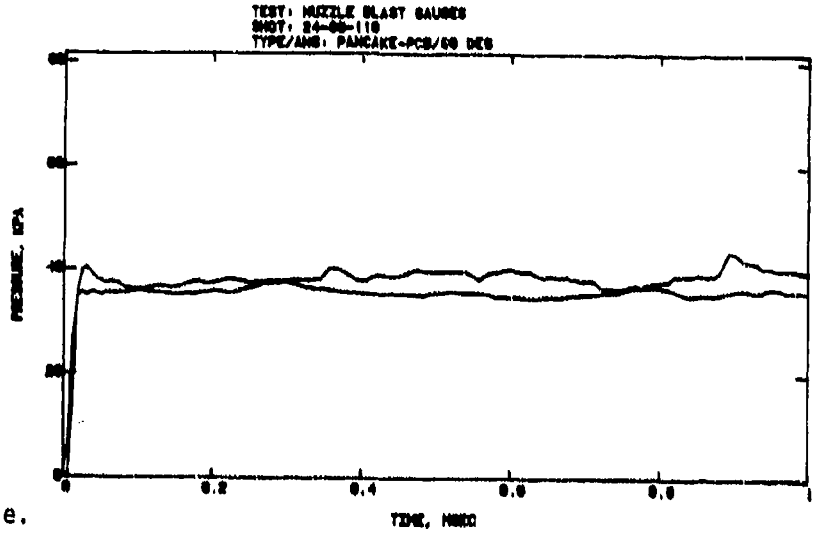


c.

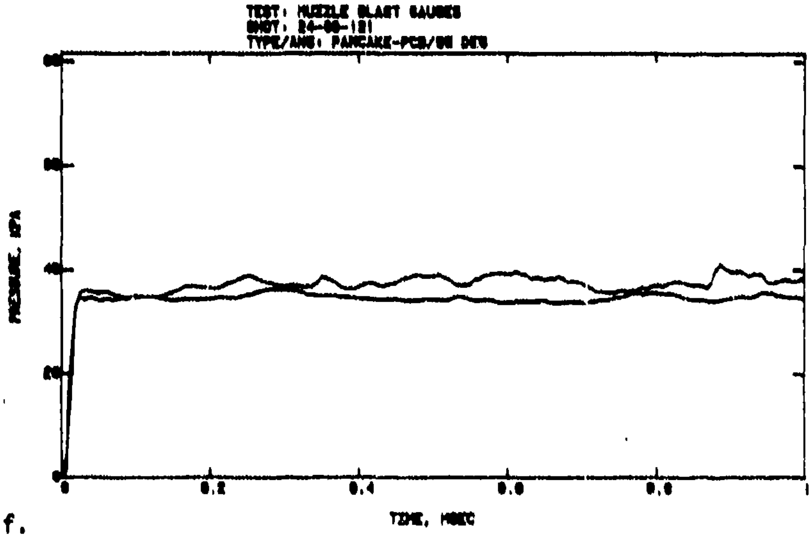


d.

Figure 13. Continued

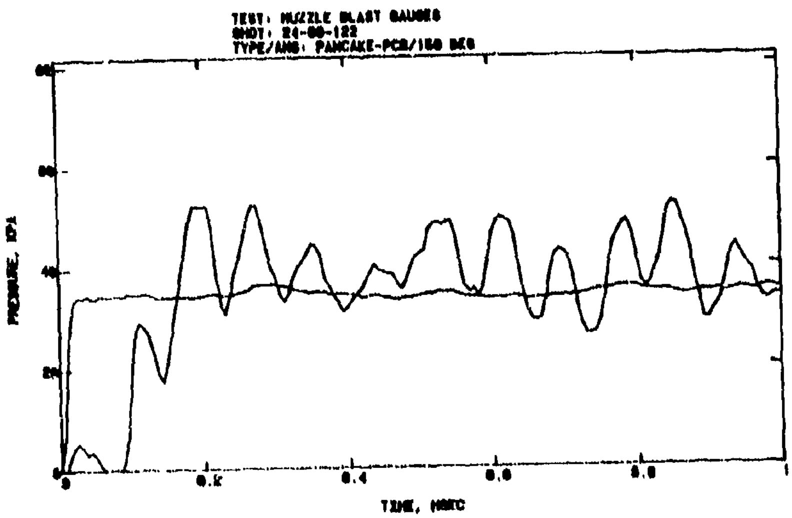


e.



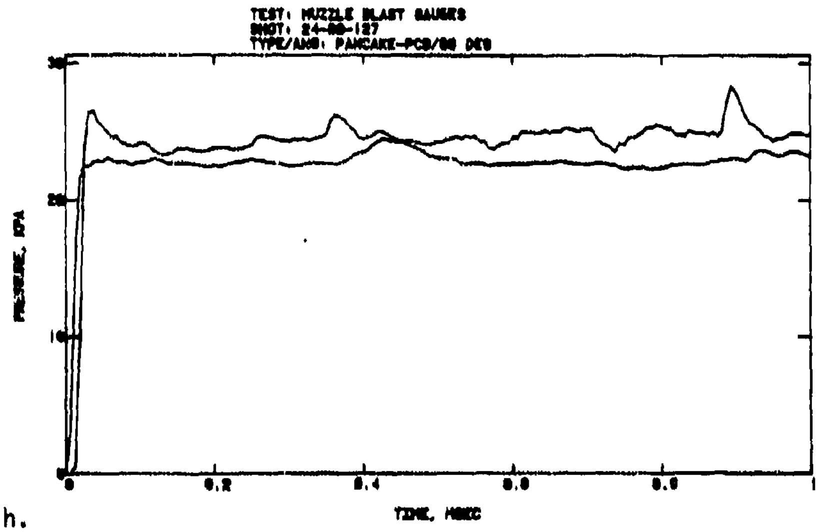
f.

Figure 13. Continued

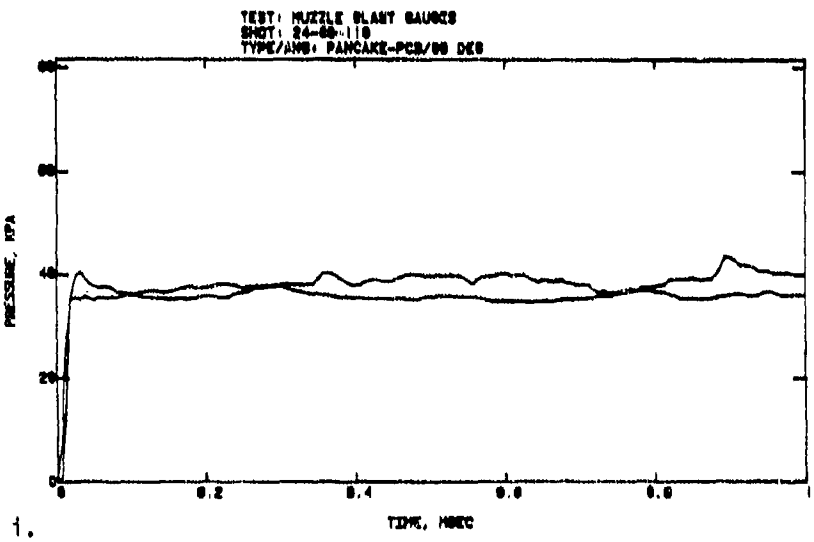


g.

Figure 13. Continued

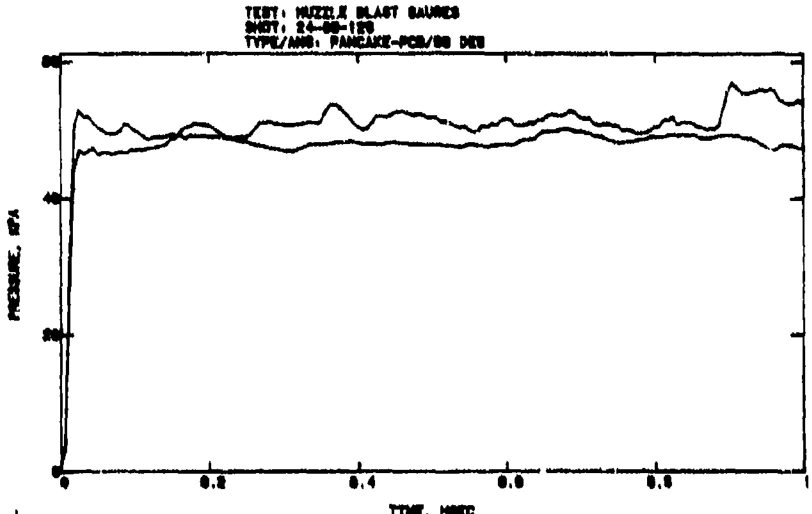


h.

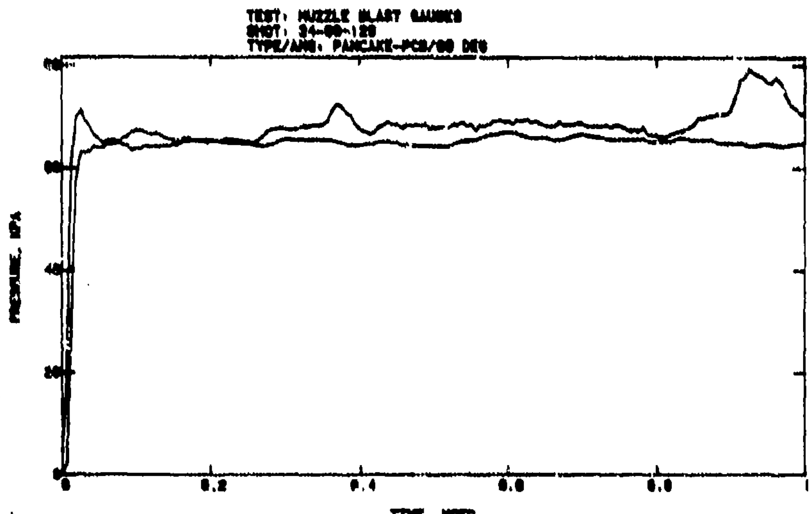


i.

Figure 13. Continued

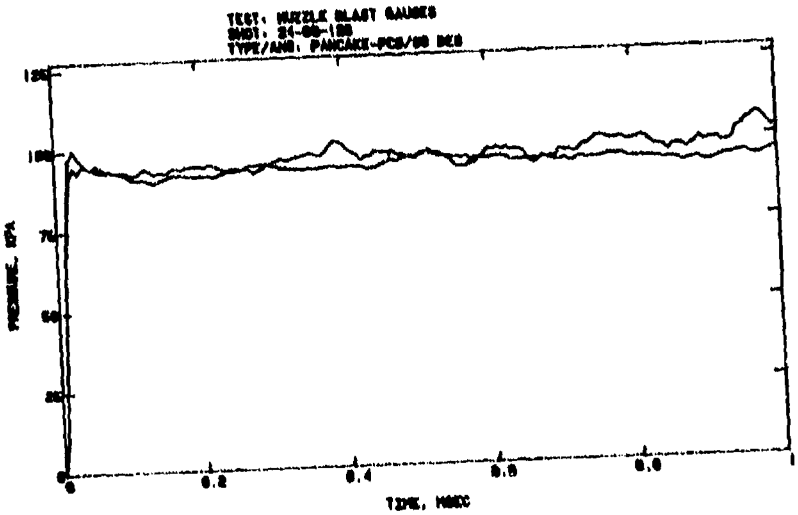


j.



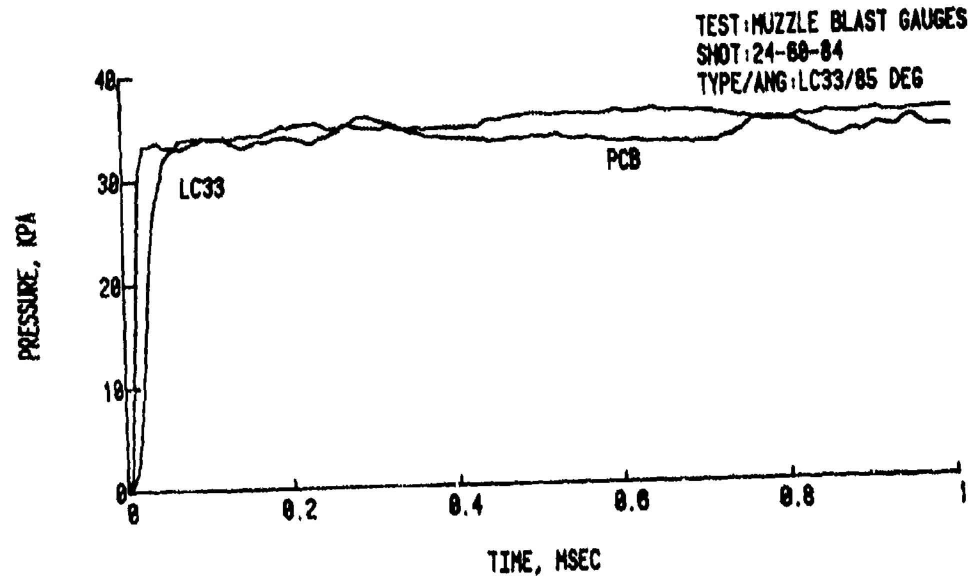
k.

Figure 13. Continued



1.

Figure 13. Continued



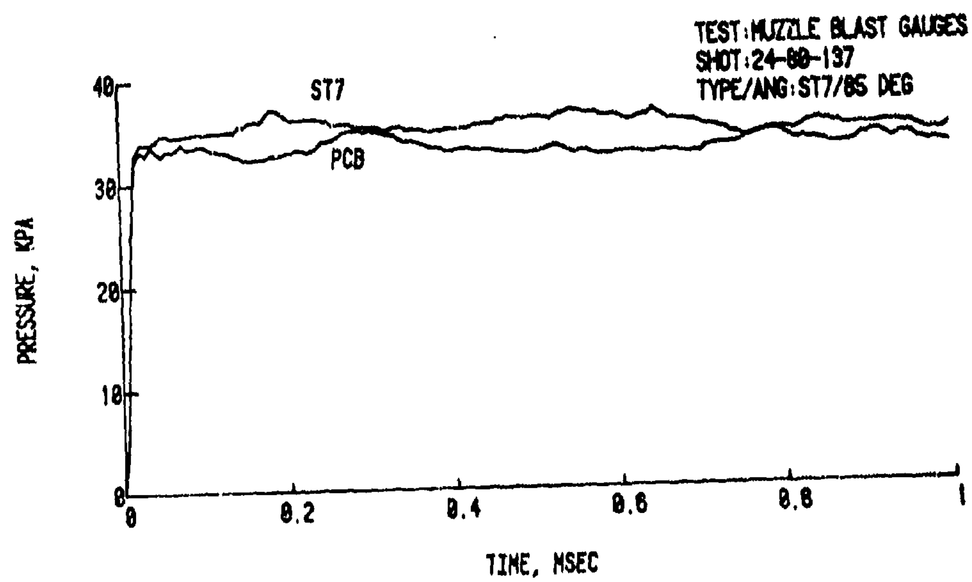
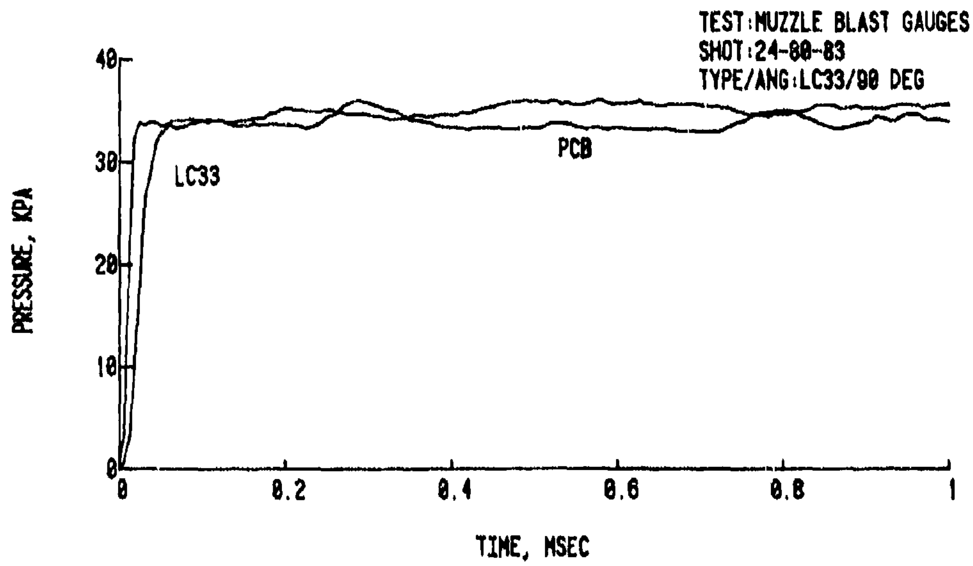
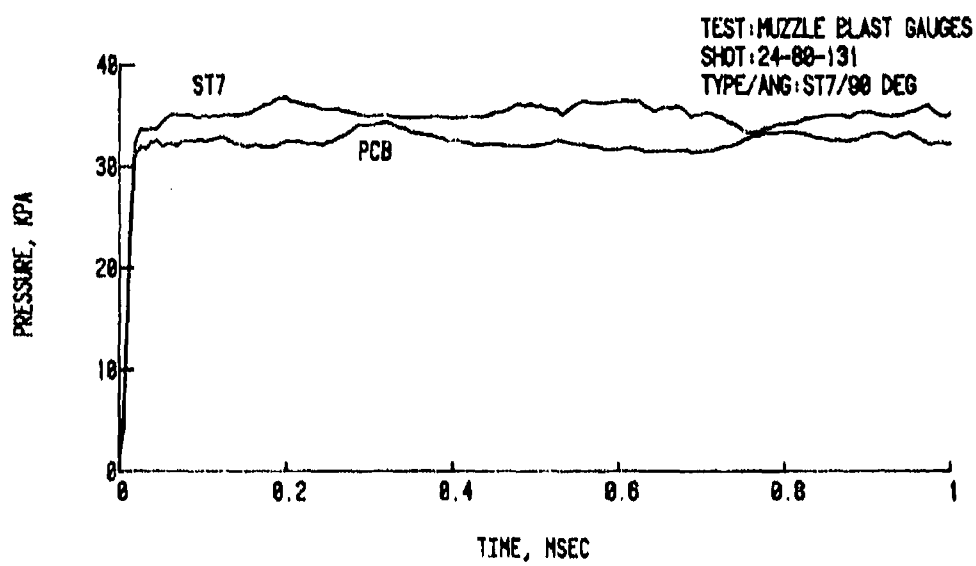


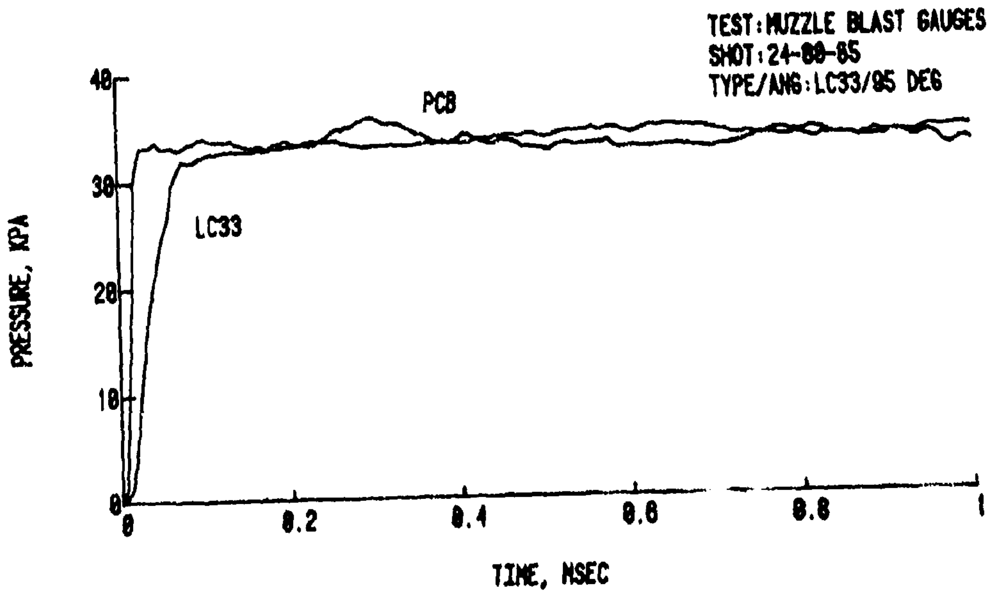
Figure 14. Comparisons for Pencil-Type Transducers, for Flow Near Grazing Incidence

a. At 85°

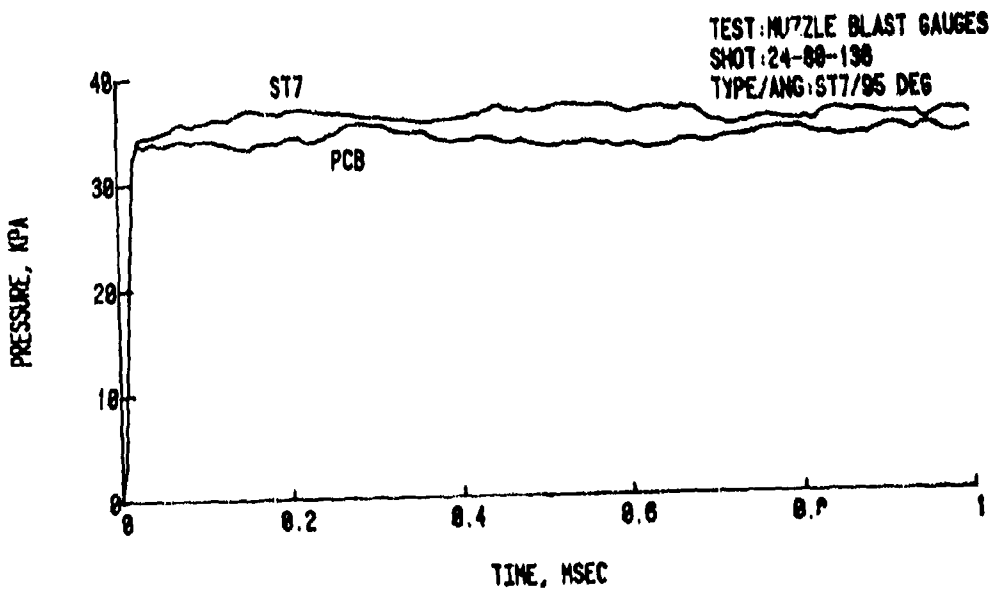




b. At 90° or Grazing



TEST:MUZZLE BLAST GAUGES
SHOT:24-80-65
TYPE/ANG:LC33/95 DEG
PCB
LC33
PRESSURE, KPA
TIME, MSEC



TEST:MUZZLE BLAST GAUGES
SHOT:24-80-130
TYPE/ANG:ST7/95 DEG
ST7
PCB
PRESSURE, KPA
TIME, MSEC

c. At 95°

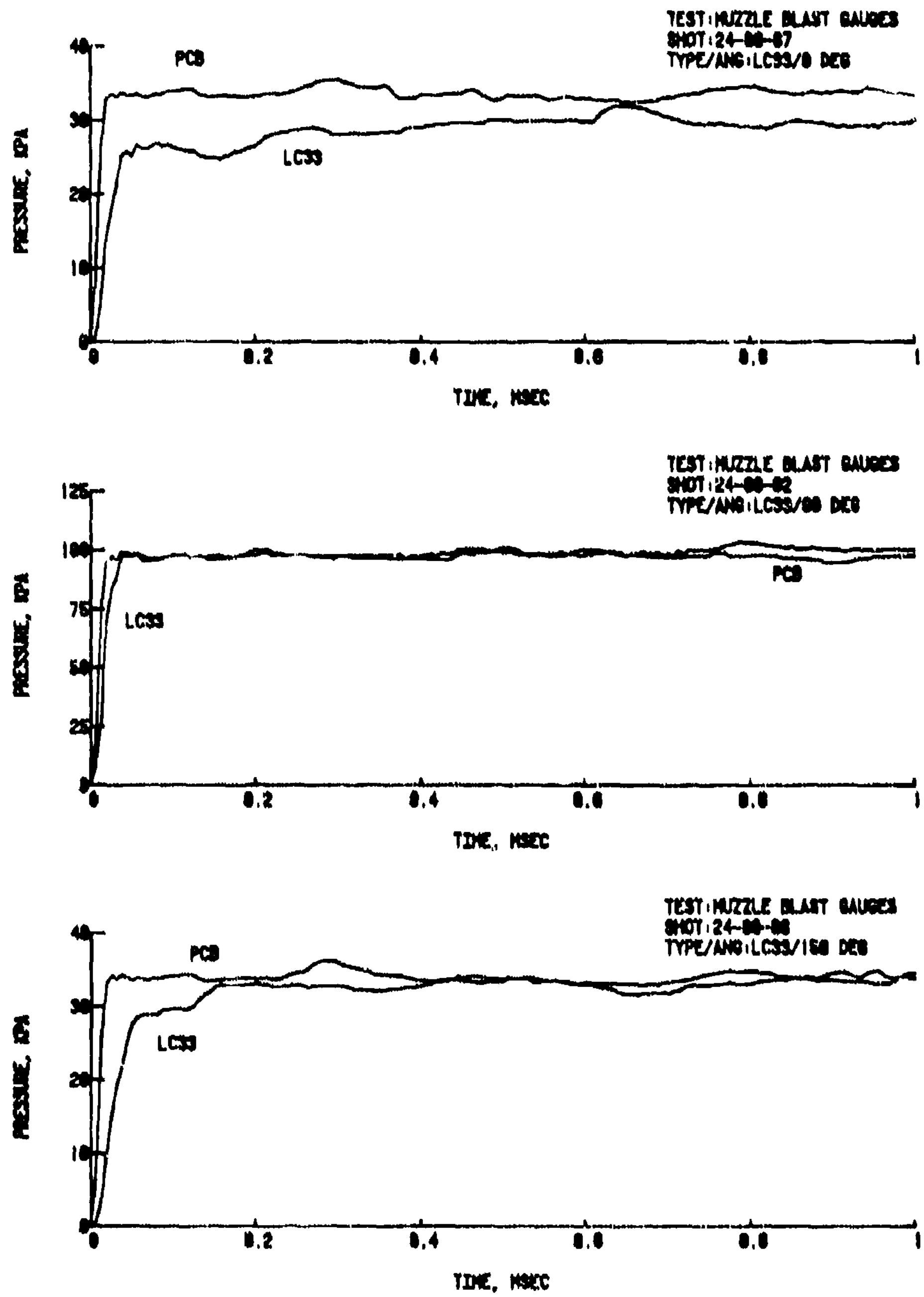
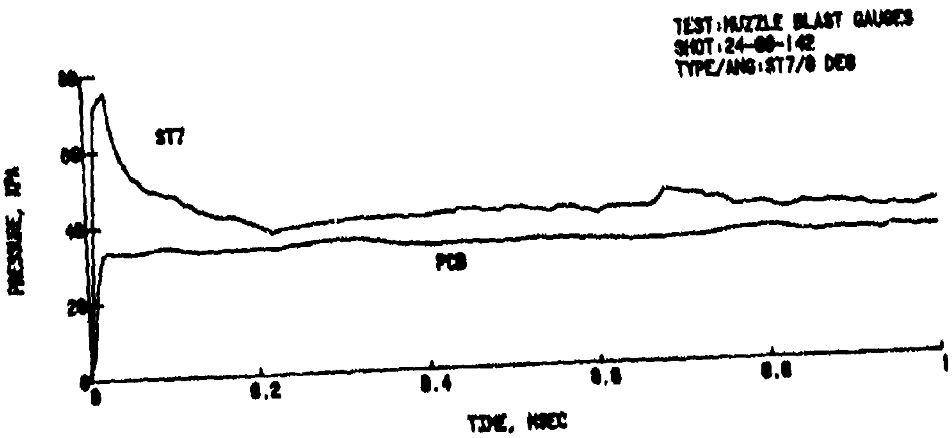
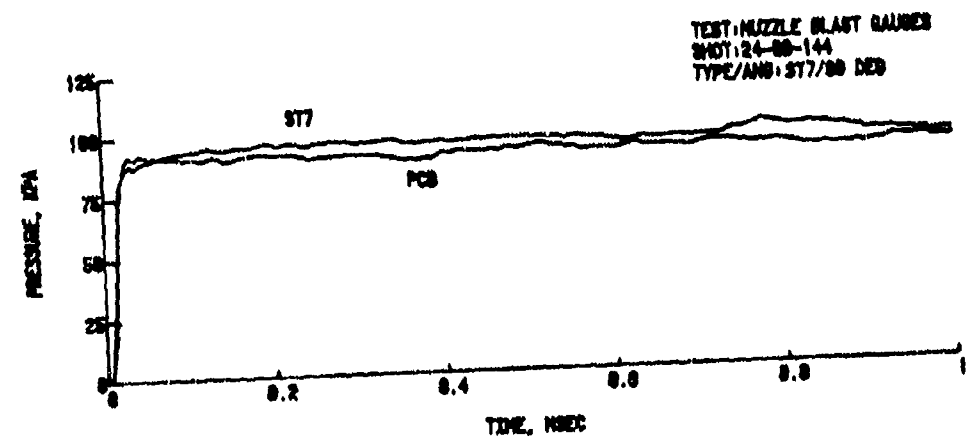
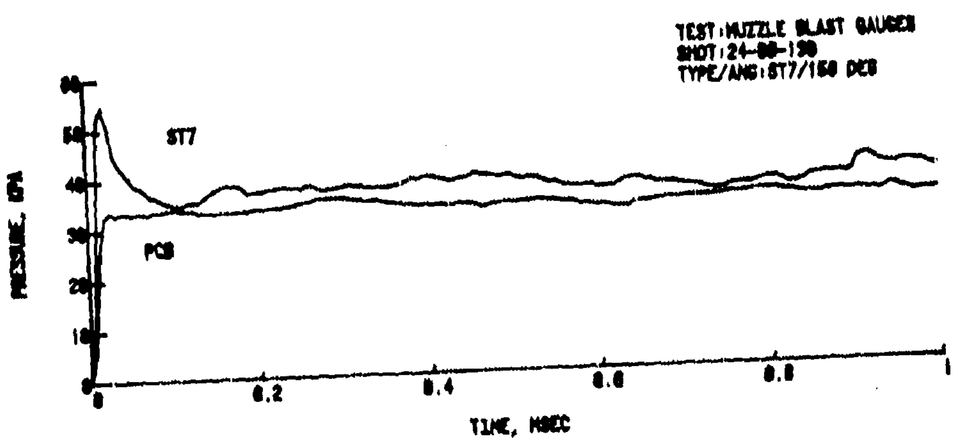


Figure 15. Deviation from True Side-on Pressure Pencil Transducers

a. LC-33


TEST:MUZZLE BLAST GAUGES
SHOT:24-88-142
TYPE/ANG:ST7/0 DEG
ST7
PCB
PRESSURE, KPA
TIME, MSEC


TEST:MUZZLE BLAST GAUGES
SHOT:24-88-144
TYPE/ANG:ST7/90 DEG
ST7
PCB
PRESSURE, KPA
TIME, MSEC


TEST:MUZZLE BLAST GAUGES
SHOT:24-88-150
TYPE/ANG:ST7/150 DEG
ST7
PCB
PRESSURE, KPA
TIME, MSEC

b. ST-7

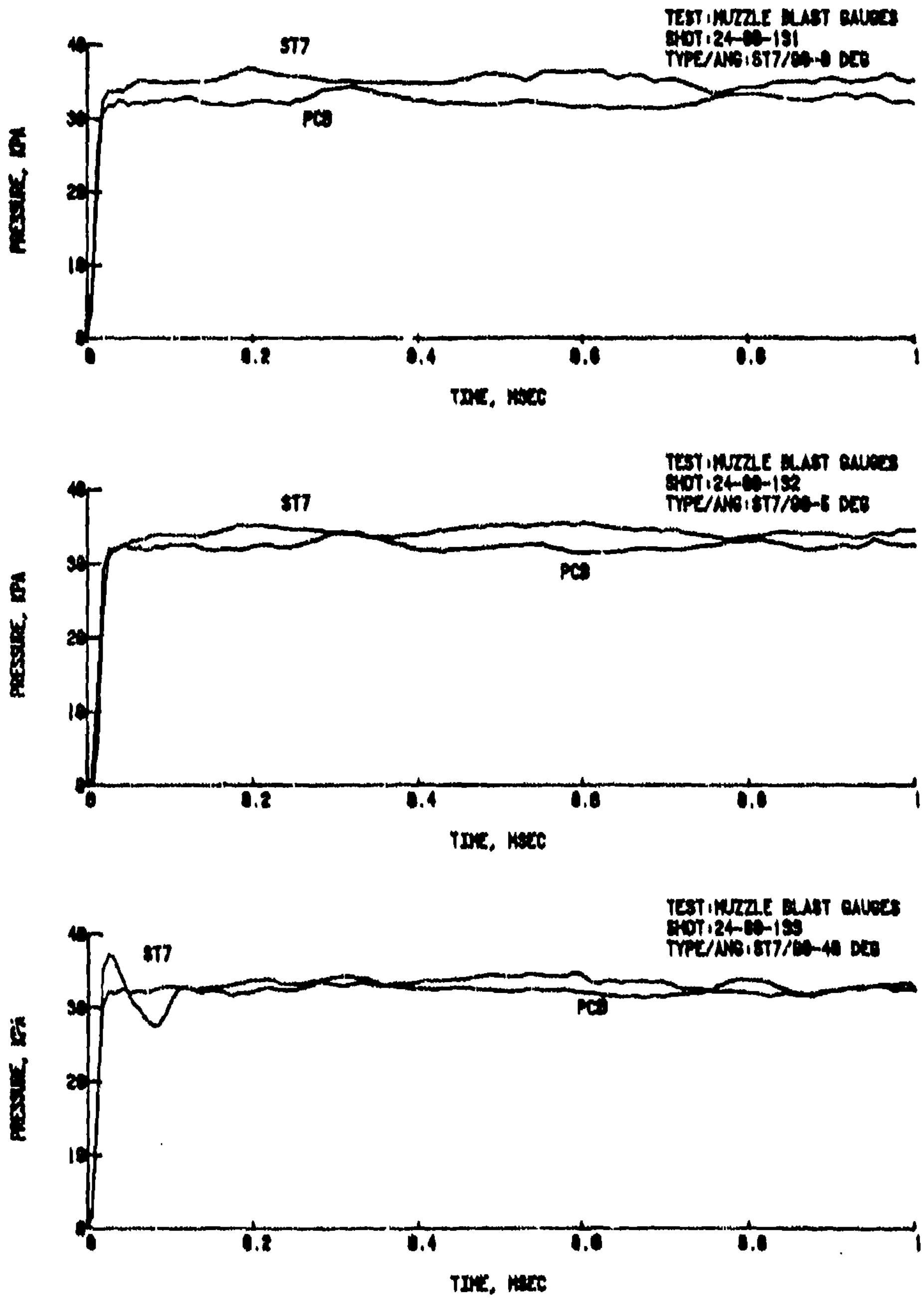


Figure 16 a. Pencil Transducer ST-7 at Various "Yaw' Angles to Grazing Incidence Flow

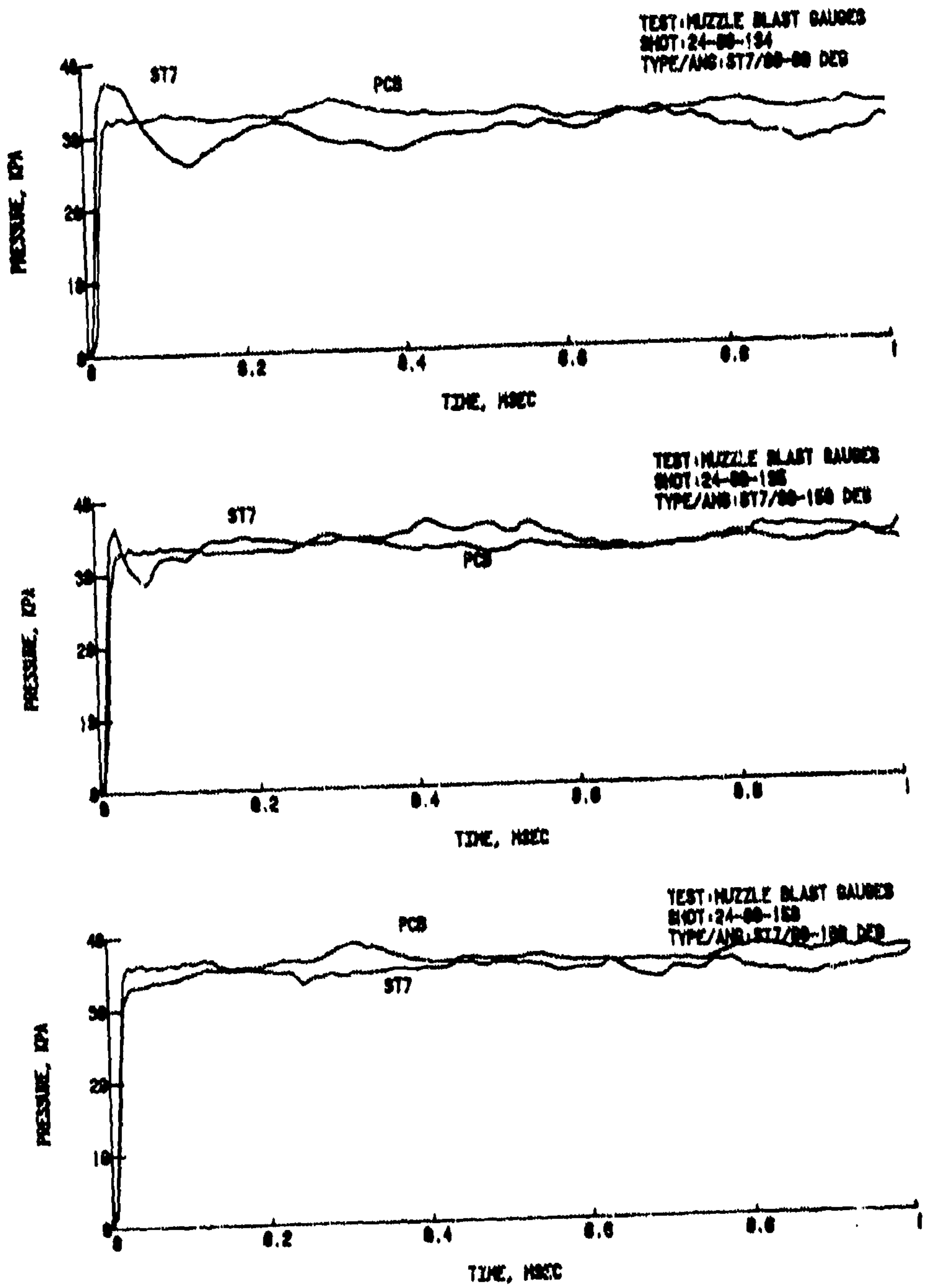
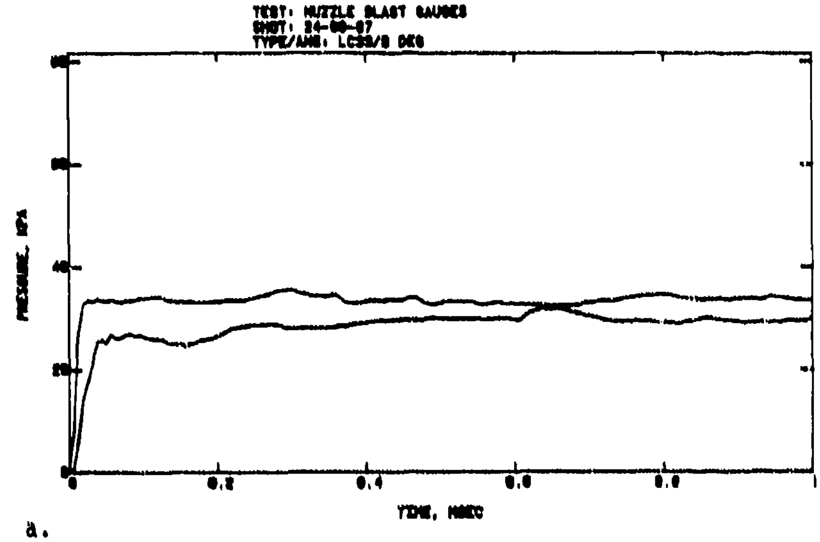
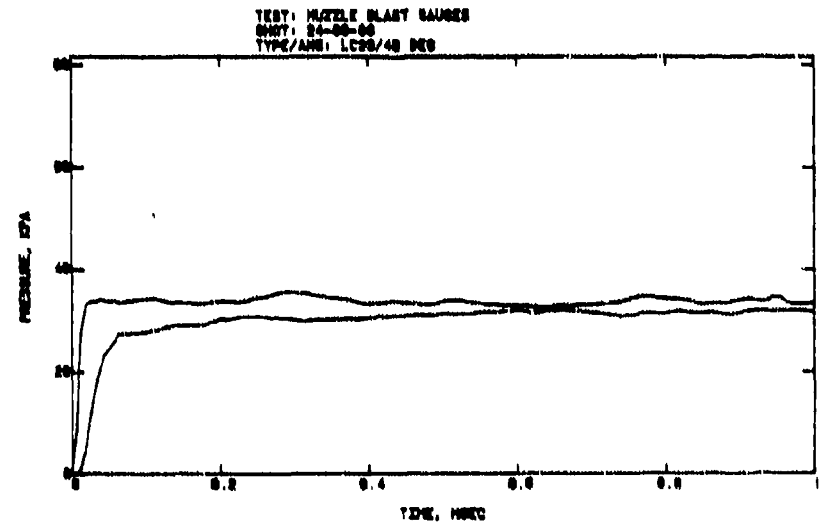

TEST:MUZZLE BLAST GAUGES
ST7
PCB
PRESSURE, KPA
TIME, MSEC
TEST:MUZZLE BLAST GAUGES
ST7
PCB
PRESSURE, KPA
TIME, MSEC
TEST:MUZZLE BLAST GAUGES
PCB
ST7
PRESSURE, KPA
TIME, MSEC

Figure 16 b.

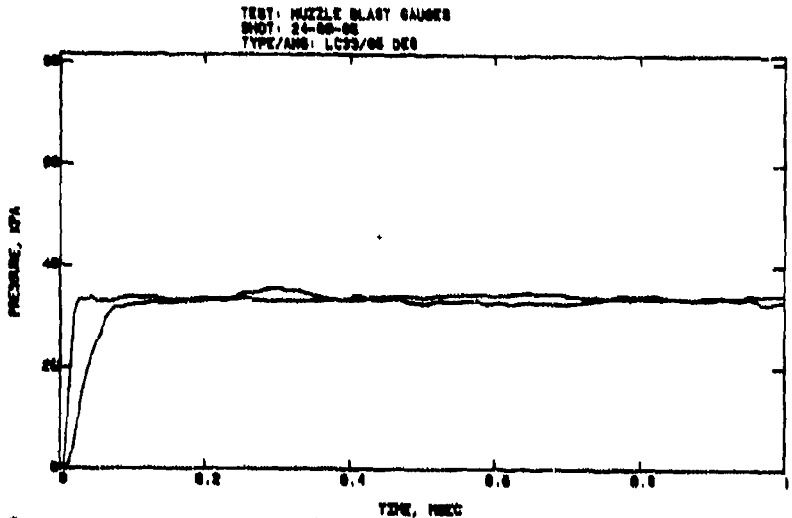


a.

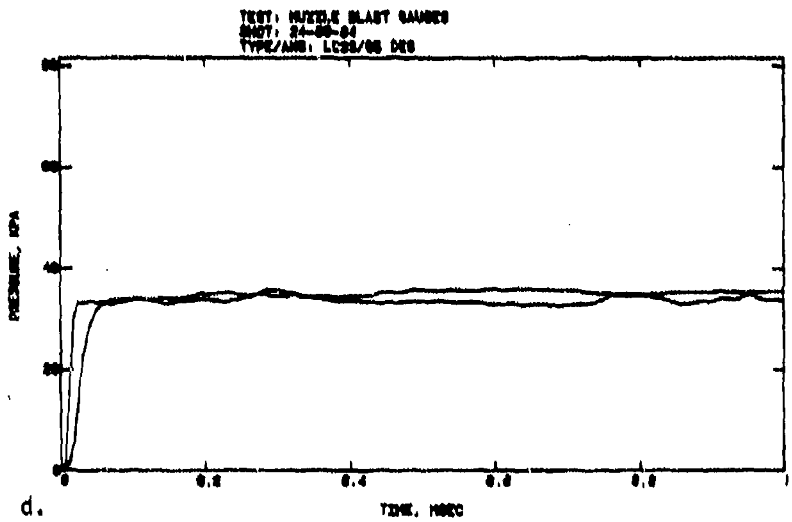


b.

Figure 17. Shot Series for LC-33 Pencil-Type Gage

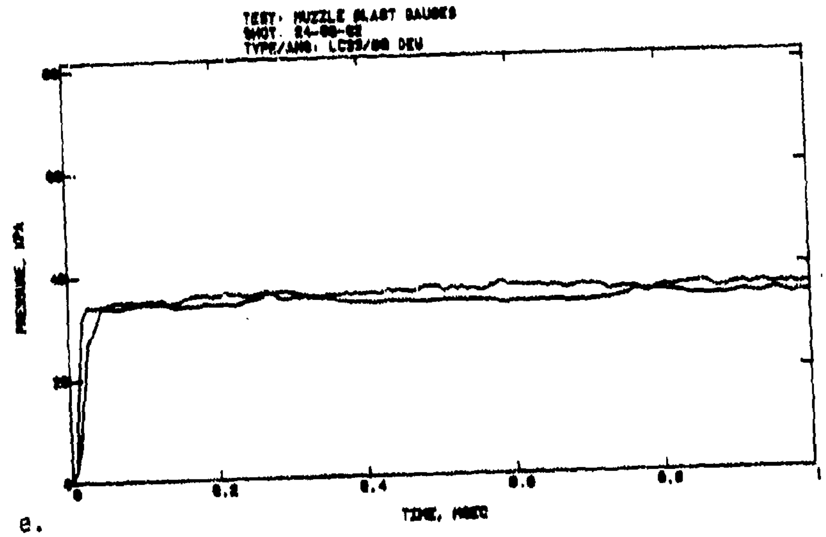


c.

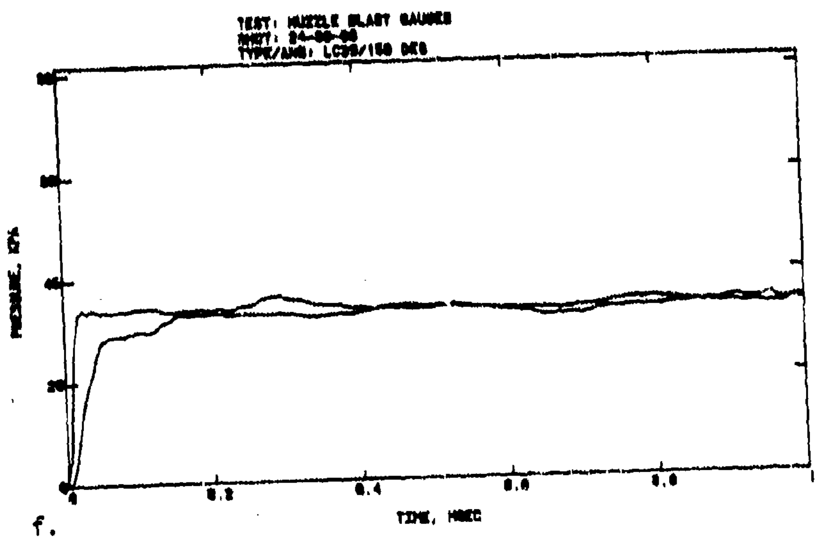


d.

Figure 17. Continued

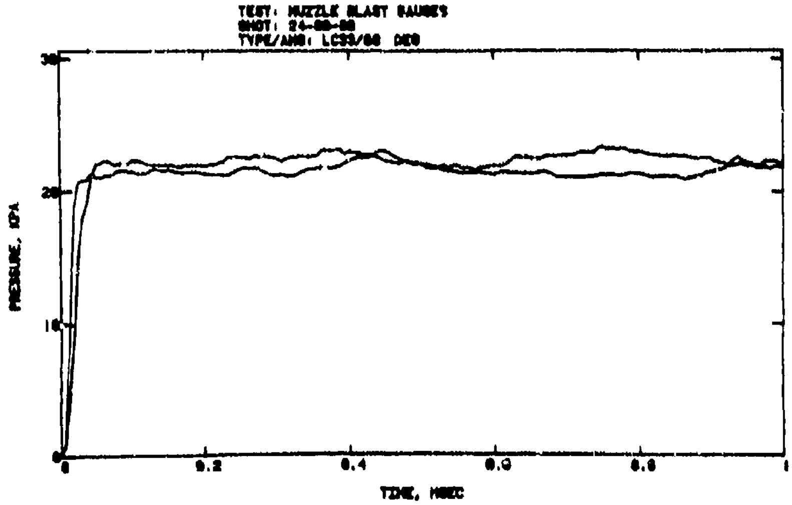


e.

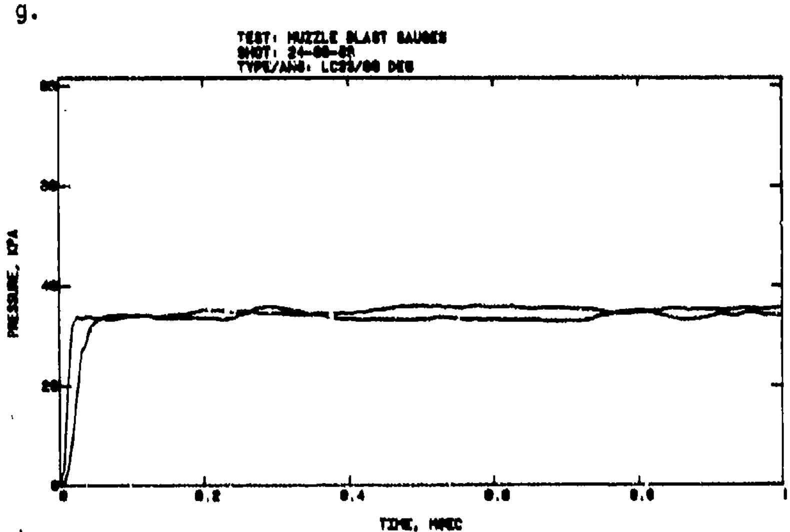


f.

Figure 17. Continued

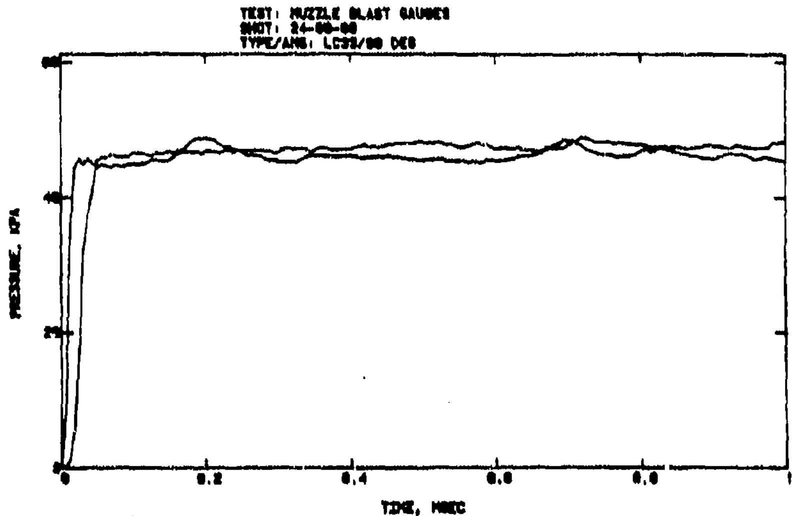


g.

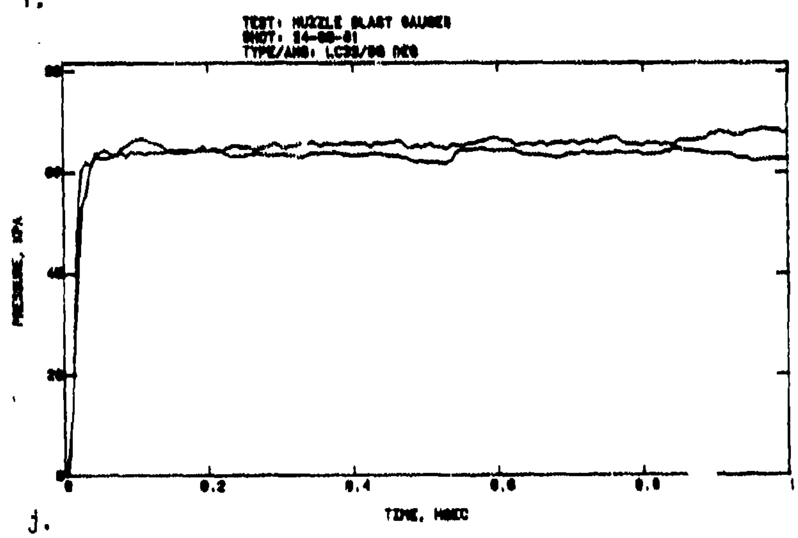


h.

Figure 17. Continued

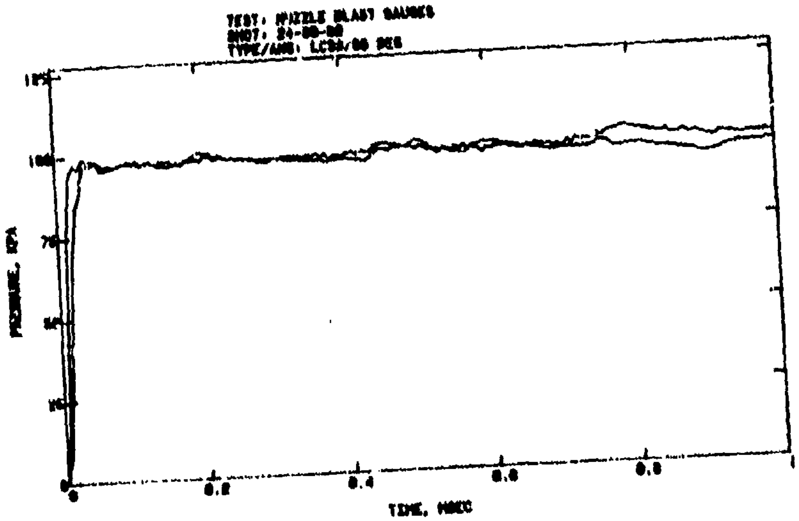


i.



j.

Figure 17. Continued



k.

Figure 17. Continued

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3. J. von Neumann, "Oblique Reflection of Shocks," Bureau of Ordnance Explosives Research Report 12, 1943.

4. H. Polachek and R. J. Seeger, "Regular Reflection of Shocks in Ideal Gases," Bureau of Ordnance Explosives Research Report 13, 1944.

5. S. Glasstone (Editor) The Effects of Nuclear Weapons, DA Pam. 39-3, April 1962.

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